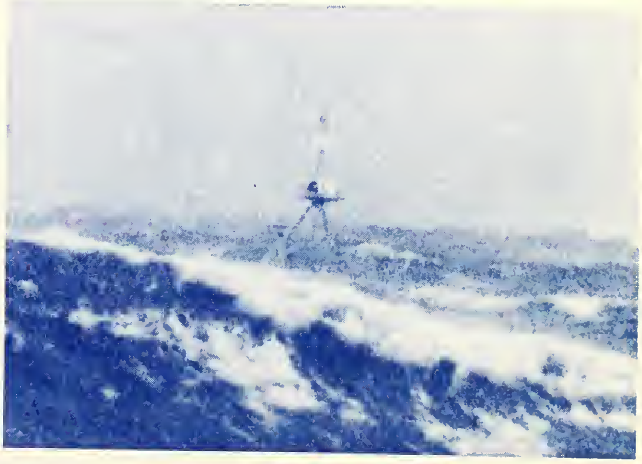
An Introduction to

SEA STATE FORECASTING

GRAHAM P. BRITTON
Captain, Royal Navy (Retired)

edited by: Kenneth E. Lilly, Jr.
Commander, NOAA



U.S. DEPARTMENT OF COMMERCE
National Oceanic and
Atmospheric Administration
National Weather Service

Cover photographs: The 120 foot trawler *American Eagle* rides out high seas in the Gulf of Alaska about 100 miles east of Kodiak Island on 22 February 1975. Winds were steady at 70 knots from the south. (Photographs used by permission of Reidar Tynes, skipper of the *American Eagle* based out of Seattle, Washington.)

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For Sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402

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Printed 1981

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Key to Symbols

A - Wave amplitude
c - Speed of propagation of a wave in shallow water
C - Speed of propagation of a wave in deep water
d - Depth of water
e - Exponential constant = 2.71828
e_a - Vapor pressure of air
e_w - Vapor pressure corresponding to the sea surface temperature
E - Wave energy per unit area (displacements in feet)
E_1 - Wave energy per unit area (displacements in meters)
E_k - Kinetic energy of surface wave
E_p - Potential energy of surface wave
f - Coriolis coefficient $= 2\Omega \sin \phi$
f - Wave frequency
$\bar{f}$ - Mean frequency in a wave spectrum
f_{max} - Wave frequency corresponding to the peak of the spectrum
g - Acceleration of gravity
H - Wave height
$H_{1/10}$ - Average height of the ten percent highest waves
$H_{1/3}$ - Significant wave height or the average height of the third of the highest waves in a record
$\bar{H}$ - Average wave height
I_o - Moment of zero order under the curve of a wave spectrum
I_n - The nth order moment of a wave spectrum
j - Steepness paramenter
k - Wave number $= 2\pi$/wave length
l - Wave length of a wave in shallow water
L - Wave length of a wave in deep water
L_o - Wave length corresponding to the maximum period in a wave spectrum
P - Atmospheric pressure
Q - Effective heat gain or loss in calories/sq cm/hour
Q_I - Effective heat input from solar radiation
Q_E - Effective heat loss due to evaporation
Q_B - Effective heat loss due to back radiation
r - Radius of curvature of isobars
R - Gas constant
(RH) - Relative humidity
s - 2π/wave period in seconds
$S(f)$ - Wave spectrum density as a function of frequency
t - time
T - Air temperature. T_s(or SST) - sea surface temperature. T_{dew} - dew point temperature.
T - wave period.
T_p(or T_{max}) - Maximum period in the spectral diagram
u - Horizontal wind speed downstream
U - Wind speed. U_{gs}-geostrophic wind speed. U_{gr}-gradient wind speed.
U_z - Horizontal wind speed at a height of Z meters
w - Vertical wind speed component
z - Vertical distance below the sea surface

α - Wind vector

β - Current vector

σ - Standard deviation

Σ - Denotes the sum of a number of quantities

ϕ - Latitude angle

ϱa - Air density

ϱs - Air density corresponding to the sea surface temperature

τ - Internal shear stress or vertical transport of horizontal momentum

Ω - Angular velocity of rotation of earth (7.29×10^{-5}rad per sec.)

θ - Potential temperature

θ_w - Wet bulb potential temperature

θ_v - Virtual potential temperature

π - Radian measure = 3.1416

$\tanh x$ - Hyperbolic tangent

$\cosh x$ - Hyperbolic cosine

$\sinh x$ - Hyperbolic sine

$\propto$ - Proportional to

Acknowledgements

The editor is grateful to a number of persons and organizations that assisted with this publication: Dr. Glenn A. Flittner, Chief, Ocean Services Division at the national headquarters level of the National Weather Service, who gave his full support to this project and the backing it needed to see it to completion; Rear Admiral E. D. Stanley, Jr., USN (ret.) and Commander Charles L. Gott, USN (ret.) of the Sea Use Council in Seattle for their assistance in locating many of the original documents and photographs used by Captain Britton; D. A. Faulkner and F. Eddy of the Canadian Atmospheric Environment Service and John Zimmerman of the NWS Forecast Office in Seattle for their constructive review of the 1977 version of the book; Joy Golly and Gini May of NOAA's Pacific Marine Environmental Laboratory for their assistance in redrawing many of the figures from the 1977 version of the manuscript; the Canadian AES for supplying the data from Ocean Weather Station PAPA; the World Meteorological Organization for kindly permitting various excerpts to be published from WMO Document 446, *Handbook on Wave Analysis and Forecasting*. Finally, a special thanks is due to all the many people within NOAA who supplied data and suggestions, especially those at the NOAA Data Buoy Office and my colleagues at the NWS Forecast Office in Seattle.

Foreword

It was my fortune to have worked closely with Captain Britton from 1975 to 1977 during his assignment with the Sea Use Council in Seattle. During this period he was tasked with helping the National Weather Service improve its services to the mariner and to establish the foundation for what was later to become the Seattle Ocean Services Unit. We met at the NWS Forecast Office in Seattle where I had just recently been assigned as the NWS representative in this endeavor.

He brought extensive ship and marine science experience with him. He graduated with honors in 1932 from Oxford University, England with a masters degree in mathematics and joined the Royal Navy in 1936 where he specialized in meteorology and oceanography until his retirement in 1968. His diverse assignments gave him a very broad perspective of all aspects of the marine environment and the effects it has on those who go to sea or are subject to its forces. Among his assignments were: Meteorological Officer aboard the *H. M. S. Shropshire, H. M. S. Warspite,* and *H. M. S. Formidable;* Officer-in- Charge of a South Atlantic meteorological station; Staff Meteorological Officer to the Mediterranean Admiral of the Fleet; Staff Officer with the Commander-in-Chief of the Home Fleet; Director of Naval Education on loan to the Royal Australian Navy to establish a degree course in meteorology and oceanography for cadets; Director of Meteorological and Oceanographic Services in the Ministry of Defense.

His activities in ocean environment research in the Royal Navy and after his retirement included investigating the use of dyes underwater for the delineation of thermoclines; the use of bathythermograph observations at ocean weather ships for the study of internal waves; studies of meteorological conditions in the boundary layer over the ocean using special radiosondes and rocket smoke tracers; studies of storm tide surges in the "Save Venice" project; and studies of air-sea interaction processes for NATO in the western Mediterranean Sea.

Upon retiring from the naval service, he taught meteorology and physical oceanography at Reading University in England and was also appointed Director of the Symposium on Maritime Meteorology with the World Meteorological Organization in 1974 for the purpose of instructing marine meteorologists in North Africa and Europe. He also served as chairman of the W.M.O. and International Oceanographic Commission committee to investigate methods of estimating and measuring rainfall over the oceans. A tireless worker and enthusiastic in his pursuits, he wrote many papers on meteorology and oceanography and was awarded the Boyle-Somerville prize in 1953 for his manuscript, *Synoptic Sequences of the Southern Oceans.* A most striking trait about Captain Britton was his willingness to seek new challenges, and so he took a leave of absence from Reading University to accept an assignment with the Sea Use Council in Seattle from 1975 to 1978. He died on April 16, 1978 at the age of 65 in London after a lingering illness.

Captain Britton's wide range of experience on almost all major oceans and seas and his keen insights into the marine environment processes gave all of us who knew and worked with him a rare opportunity to learn much about this fascinating area of science. He believed that only through the co-operation of meteorologists and oceanographers could the best environmental products for the mariner be produced. It was vital that persons in each profession have a working knowledge of the other discipline.

Improvements in services and forecasts usually come in small steps, much of which depend on the training of meteorologists and oceanographers and their understanding of the problems faced by the mariner. It was a fact that up to about 1976 few marine forecasters had any comprehensive training in sea state forecasting or the effects oceanic processes have on the atmosphere. Most marine forecasters were persons with backgrounds in aviation weather and over-the-land forecasting techniques. It was toward this end — the training of marine forecasters — that Captain Britton was working when he died. He put a great deal of effort into helping establish and teach a special training course for professional forecasters at the Naval Post Graduate School in Monterey, California. This course has been taught at various times to dozens of forecasters. This book was part of Captain Britton's efforts in training meteorologists because he recognized that few, if any, books dealt with the practical interrelationships between oceanography and meteorology.

This is not a theoretical textbook for the most part, but a practical guide that can be used by any meteorologist or oceanographer involved with predicting the marine environment or providing services to mariners. It is based on many ideas and techniques Captain Britton had accumulated over the years. Many of the physical principles are illustrated by actual examples. Too often these days, the scientist relies more and more on computer produced products and misses the flavor of manipulating data with his personal touch to make the best forecasts or marine product he can. Captain Britton perceived that reliance entirely upon computer products without looking at the data upon which they are based often results in poor service to the mariner.

In this book, he takes us away from the machine and gives us the means of looking at the marine environment as he saw it. We will always be able to combine these insights with modern day numerical techniques now in use.

The original version of this book was published in October 1977 by the Sea Use Council under a contract with the National Weather Service. On a subsequent assignment to the NWS Forecast Office in Seattle in 1980, I agreed to edit the manuscript into finished form, and, for the most part, have left the text as Captain Britton wrote it, preserving the context of his thoughts as much as possible. Almost all the diagrams have been redrawn from copies in the original version. It is in memory of a talented meteorologist (and oceanographer), a patient teacher, and most of all, a close friend, that this book is dedicated. I hope that you, too, will appreciate the insights of a true marine scientist.

Seattle, Washington
1980

Kenneth E. Lilly, Jr.
Commander, NOAA

Preface

Forecasting the development of sea and swell is a specialized technical task for a meteorologist or an oceanographer. To undertake this task satisfactorily it is desirable that this specialist has some background experience which combines observational assessments to back his theoretical knowledge. There are comparatively few experts who have had this necessary dual training combining mathematical skill with practical experience.

At the Regional Training Seminar held in Rome in April 1974 on ''Meteorological Services to Marine and Coastal Activities'' the recommedation was made to the World Meteorological Organization of the need for a review of the many existing methods of forecasting sea and swell and the production of a booklet rationalizing and summarizing much of the detail. In consequence a small committee of experts was set up, and a *Handbook on Wave Analysis and Forecasting* has been published (W.M.O. Document No. 446) that meets the requirement admirably for the technician with some knowledge of meteorology and with a mathematical background.

Unlike the W.M.O. publication, this book is intended as an introductory volume without too much of the detail and aims to treat the subject descriptively. Hence, it has a strong practical bias. As far as possible, theory is avoided and mathematical treatments are relegated to an appendix. In this way it is intended to cater to university students who have never been to sea and may not appreciate the numerous factors involved and as a training manual for meteorologists who were not given any special training in marine meteorology during their indoctrination courses.

It is intended that the book be supplemented by some practical exercises using series of synoptic chart sequences for the ocean areas and spectral data from buoys and weather ships. The reader then has the opportunity to analyze the weather charts himself and make his own sea and swell forecasts or to derive the skill to use computer outputs relayed by facsimile from national weather services to the best advantages for his particular need.

Seattle, Washington
1977

Graham P. Britton
Captain, Royal Navy (ret.)

CHAPTER

1

THE PROBLEM OF SEA AND SWELL FORECASTING

1.1 Introduction. There are many good papers on waves and various manuals and methods dealing with the forecasting of sea and swell. It is a subject which mainly concerns the specialist in energy exchange between the atmosphere and the ocean, but it does not lie exclusively within the province of either the meteorologist or the oceanographer and, hence, does not always receive due attention in the operational training programs for the respective disciplines. By its very nature, the subject is a complex one, perhaps best explained by liberal use of higher mathematics. In consequence, it is usually found that books dealing with sea and swell are either theoretical or are lacking in descriptive treatment. The aim of this work is to show the practical relationship between the atmosphere and the ocean.

To provide the best services to ships, it is desirable for the originators of forecasts to have some practical experience in observing sea and swell and at least possess the capability to distinguish between the two if called upon to do so. Often this is not the case, for the task usually falls upon a meteorologist who has probably never been to sea and perhaps never received a course in marine meteorology. Even so, those called upon to exercise forecasting responsibilities often have to do so for only a limited area or for one particular facet of the subject for a limited time. Different techniques are required when forecasting for the open oceans, the semi-closed seas, and coastal waters.

Very seldom is sufficient experienced manpower available in meteorological offices to undertake all possible tasks satisfactorily. The root cause of this deficiency has been the tendency to regard meteorology and oceanography as different scientific disciplines. There is some justification in practical applications since the time and distance scales of events are usually of a different order of magnitude. Hence, the boundary layers in both media never properly belong to either one or the other specialist. The classical oceanographer usually likes to be well down below the seasonal thermocline before being in his element and the meteorologist prefers to work above the geostrophic level. (The technical terms seasonal thermocline and geostrophic level will be explained in detail later.) The requirement is for a technical expert, who, while possessing considerable knowledge of the dynamics of both media, specializes in interaction aspects of the top 50 meters of the ocean in conjunction with the lowest 500 meters of the atmosphere. These limits are open to some question and dispute but almost all practical events of consequences occur within these two strata to affect the welfare of shipping and the livelihood of fishermen.

Meteorological training in most countries of the world seeks to provide forecasters with the basic capability to understand the potential impact of the weather on operational procedures in various industries such as aviation, construction, transportation, and so on with the forecasters acquiring experience for specific tasks by on-the-job training. For this an understanding of the dynamics of the atmosphere is usually sufficient. But the task of forecasting sea and swell involves not only the dynamics of the atmosphere but also the dynamics of the sea, and in events involving damage or disaster, the atmosphere is only the indirect cause, and it is the sea which is invariably the more destructive element. To undertake the job efficiently, a meteorological forecaster needs some basic training in currents and tidal movements. But seldom is sufficient time made available in meteorological training courses for such items. In consequence sea and swell forecasting is treated by weather services almost exclusively as a meteorological problem to be solved using numerical models based on the dynamics of the atmosphere. Since only half the problem is thereby considered, the results are seldom satisfactory, particularly in coastal waters where shipping is most vulnerable.

1.2 The nature of the problem. The first time a child throws a stone into a pool of water and watches the ripples spread outward over the surface, he witnesses a chain reaction of events which is both fascinating and varied. A wave's progress, which is seemingly orderly and symmetrical at first, changes when the ripples move into shallow water. As the concentric rings approach the shore, the waves increase in height a little until the crests finally roll over and break. It follows that the depth of the water is an important factor in the progress and behavior of waves. The observant child will also notice some change in direction of propagation when the waves reach the shallows.

When the first puffs of wind blow over a calm sea, they cause the formation of small capillary waves. These usually appear when the wind reaches a speed of about 3 knots. The glassy appearence of the sea partially disappears -not uniformly, but in patches; the capillary waves creating the impression of a discoloration of areas of the water surface. These capillary waves have a wave length of a few centimeters only, but in almost all circumstances they behave like deep water waves. This is because the ratio of the wave length to the depth of water is small even when comparatively close to the shore. This to some may seem paradoxical, particularly as tsunamis (very long waves created by earthquakes in the ocean bed) behave as shallow water waves even in the deepest oceans.

As the wind increases in strength, the capillary waves increase in height and length; gravity waves are formed with small capillary waves superimposed on them. At a critical wind speed of about 13 knots an important change takes place in the energy transfer process from the atmosphere to the ocean. Foam and whitecaps appear and the sea takes on a much more random or chaotic state. Whenever the surface skin of the water is broken, a parcel of energy escapes from the ocean and is transferred to the atmosphere. The evaporation process requires energy to be taken from the sea to transform water into water vapor. It may be regarded as the creation of a type of fuel, which is frequently transported at a relatively fast rate to higher latitudes by the winds, where it is ''burnt'' as rainfall or expended in increasing the vorticity of depressions.

As the wind speed increases, the waves continue to build. The height of the waves increases relatively faster than the wave length, but after a certain time the height rate slows down and the wave length steadily increases. Theoretically, equilibrium is reached when the speed of the waves equals the speed of the wind. If the wind speed continues to increase, as it will do periodically in gusts at gale force, the crests are torn off the waves and quantities of spray are projected into the atmosphere.

Thus, at a certain stage corresponding to a given wind stress, the growth in the height of the waves ceases. As the waves move away from the generating sphere of influence (*i.e.,* the area where wind stress was applied to the surface of the water) the character of the waves changes. The wave length may increase further as the crests become more rounded, and when this effect can be clearly observed they are designated as ''swell'' as opposed to ''sea.'' Sea state forecasting must consider separately sea and swell, the heights of which are additive, but not linearly (see section 7.5). Just outside the boundaries of localized storms, such as hurricanes or typhoons, swells of heights of the order of 20 feet may be encountered although the sea surface remains glassy and free from capillary waves in the complete absence of any local wind.

1.3 The speed of waves. When we come to deal with the theoretical aspects of waves it will be shown that the speed of waves in deep water is proportional to the wave length while in shallow water the speed is proportional to the depth of water. Thus waves of long wave length move faster in deep water than waves of short length. Long, low swells which are moving rapidly are often the first indication to the distant observer of the approach of a storm. This is a phenomenon frequently observed in the doldrums where long, low swell is easily distinguishable in the calm waters and is a good indicator of the birth of a tropical storm. Sometimes it may indicate an increase of wind strength in the trade wind belt some hundreds of miles away. The swell may arrive several hours before any increase in wind force is experienced, and on occasion swells of several feet in amplitude may be observed on glassy seas completely unruffled by the wind.

1.4 Breaking waves and surf. It can be shown that waves of all wave lengths move at the same speed in shallow water. As the depth of water decreases and a wave approaches a beach, the speed of the wave decreases, causing those waves trailing behind to gain on those ahead. This is equivalent to a concentration of more energy into a smaller surface area, and some of the kinetic energy is converted into potential energy. The waves increase in height until they finally become top-heavy and break. Inside the line of the breaking surf small craft are in danger from the weight of water descending on them.

The energy involved in breaking surf can be very great indeed, and may be of major consequence to inshore engineering works, coastal installations, sailing, or recreation.

Theoretically, a wave must break when the steepness (ratio of amplitude to wave length) is greater than 1/7, but in the open ocean the ratio seldom attains a steepness factor of 1/10 before the crests begin to curl over and whitecaps appear. Generally, waves may be considered to have a menacing character once the slope on the windward side is greater than 1/18.

1.5 The constraints - duration or fetch. Since the density of air is approximately 600 times less than that of water, it is obvious that it will take time for the lighter propelling agent (the air) to exert maximum effect on the heavier liquid (the sea). A period of time must elapse before sufficient energy can be taken out of an air stream and transferred to the sea to develop the maximum sea state.

When a wind blows from offshore, a minimum distance (fetch) must be available before the maximum deformation of the sea surface is attained. Both minimum duration and minimum fetch will vary with the degree of "bite" which the air stream exercises on the water surface, and this in turn will vary with many factors such as the state of the atmosphere, the surface water temperature, and, above all, the currents and the tides. At low wind speeds and in stable conditions the wind tends to glide or slip between layers of varying density within the atmosphere, and the wind is unable to obtain a good grip on the water surface. But as the speed increases and turbulence develops, the surface roughens, and the degree of bite increases. The really significant generating forces of sea and swell only occur as the wind speed approaches 20 knots. As a very approximate guide to a forecaster, little detailed attention need be given to significant swell periods until the surface winds approach 20 knots or more.

It will be demonstrated later that an almost unlimited number of frequencies of waves and wave periods exist in the deformations of a sea surface, but the concentration into significant spectra is seldom important until the wind approaches moderate gale force. The seas generated by winds of lesser value do not progress far outside the generating area as swell. This is not to imply that danger to small boats is unlikely at wind speeds less than 20 knots, particularly in tide ways or in strong currents in shallow waters -far from it.

In dealing with the forecasting problem, one or both of these constraints has to be considered; either the wind speed has not been operative for a sufficient length of time to cause the deformation to reach maximum proportions or the wind has not blown over a sufficient distance. The problem facing the forecaster is often to decide which is the more important consideration, the duration or the fetch in the particular case considered. The difference is not normally very much, and it is usual to consider only the one which is the greater constraint.

1.6 The problems of prediction. Predictions of wave formation and progression in the open sea are different from those in coastal waters and demand different techniques. Models for predicting surf should incorporate features of the bottom topography and the local coastline and make allowance for changes to sand bars and shingle beds caused by waves. Furthermore, the wind field in coastal areas is complicated by land and sea breezes and orographic influences.

It has been assessed that only about one third of the waves encountered at sea are fully developed for a given wind speed as a result of one or the other constraints. It is principally for this reason that it is impossible to postulate any one single method of forecasting sea and swell which will be best for a particular application. Thus, in the Mediterranean winter, conditions can be most unpleasant in short steep seas created either by localized, small-scale cyclonic disturbances or by streams of cold katabatic air emerging from the valleys and mountain passes (*e.g.*,the mistral or bora). There is hardly one single point in the Mediterranean where there is not some limitation due to either fetch or duration. To forecast most effectively it is generally better to concentrate on point forecasting as opposed to area forecasting; although such procedures impose major problems for national weather services which are geared to numerical modeling techniques to obtain wind vectors. The standard grids are often too coarse for the task at hand.

Special considerations also apply in semi-closed tidal seas such as the North Sea. Fetch is again a limitation in almost every direction (the exceptions being the north to northwesterly directions having a fetch in excess of 1,000 miles to the ice edge). But unlike the Mediterranean, the North Sea experiences tidal flows and surges which in turn affect wave behavior. There are also complications introduced by limited depths of water, thereby making it generally desirable to use point forecasting methods in preference to the area forecasting techniques employed as a basis for open ocean routings. This is particularly true when dealing with specialized forecasts for oil rig operations.

1.7 The requirement to consider currents and tides. The problem is made more complex when the wind stress is applied to a water surface which itself has some inertial movement, as for example when the wind is flowing over water which is subject to the influences of currents. When the wind flows contrary to the current, whitecaps will appear at much lower speeds than 13 knots. The bite of the wind on the water is more readily attained and the waves grow faster, are steeper, and break more readily. The effect of currents and tides is to produce complex eddy motions and a relative change in wave period or frequency; this makes the equations of motion much more complex. It is not always appreciated that the mere height of waves is of far less importance to shipmasters than their steepness (the ratio of height to wave length). When the length of the waves approximates to the length of the ship, resonant effects may arise which make the ship difficult to handle and results in some loss of speed. If, in addition, the waves are steep, the erratic motions of the ship are intensified and the chances of waves breaking over the ship are greatly increased. If the bow of the ship digs into the oncoming waves causing them to break over the ship, the unpleasant circumstances of "slamming" may occur to cause damage both to the ship and to its cargo.

A young storm during which the seas are still in course of development is often of far greater potential danger to a ship than a fully developed sea with large amplitude waves. This is because the waves are relatively steeper in the formative stages. Most ships are capable of riding waves of long wave length without noticeable difficulty for they are designed for this. It is the short steep seas which give rise to the violent motions that strain the hull or worse, cause the cargo to shift. Hence, a forecasting service for sea and swell preferably should go beyond giving general statements on the character of the sea such as "rough" or "very rough." The best forecast will provide details of expected significant wave heights and periods so that ships may assess the steepness by simple rules and see how these will apply to their particular vessel. When possible, wave lengths should be also given so that the steepness factors are more readily available.

1.8 Numerical models for sea and swell forecasts. In the major meteorological analysis centers, the trend continues to produce all chart aids by automatic means, eliminating as far as possible hand drawn analyses. So many paramaters are involved in sea and swell forecasting that it is difficult to take adequate account of all of them. In particular, since the problem is not exclusively meteorological, there are many shortcomings in the present outputs from national weather service offices in sea and swell services. In this brief review of the existing services, the open oceans and coastal waters will be considered separately.

a. Shortcomings in models for open ocean areas. Meteorologists readily recognize that isobars only approximate to the streamline flow of the wind. In particular they seldom attempt to use isobars to forecast wind speed and direction in low latitudes where the Coriolis component is small. In these regions, streamline analysis is preferred. However, pressure analysis and prognoses charts produced by primitive equations models are the primary computer outputs of meteorological organizations involved with sea and swell services.

Ideally, the sea and swell forecaster has a special requirement for an "effective wind field chart," which he can obtain only from a combination of wind speeds and directions reported by all available ships. When there is inadequate coverage of ship reports the forecaster must resort to the winds derived from pressure charts. For the task of sea and swell prediction, an effective wind field chart is only the first step. The forecaster must subsequently use the effective wind fields to compute sea and swell heights and periods by taking into consideration the fetch and duration of wind flow, sea surface temperature gradients, wind accelerations, surface currents, tides, and also precipitation. The most efficient means is still to use hand drawn analyses, but this is seldom compatible with present day policies and practices.

Hemispheric numerical surface actual and prognostic charts are not adequate for sea and swell forecasting since they suffer from the following deficiencies: (a) the grid size is generally too coarse to deduce accurate surface winds; (b) insufficient attention can be given to the actual wind values reported from ships (frequently only pressure values are considered). Owing to inevitable time delays in receipt of data, only a small percentage of ship reports are taken into account; (c) boundary layer stability, particularly at the lowest levels, cannot be deduced with any degree of accuracy; (d) frontal zones are insufficiently defined; (e) valuable satellite data are not fully used in the prognostic frontal zone analyses; (f) oceanographic features, such as thermal gradients, upper level stratifications, currents, and tides, are absent from consideration.

Without some knowledge of the prognostic air mass characteristics and the incorporation of oceanographic information, it is impossible to consider the result of changes in the effective wind on the drag coefficient.

It is not practicable or acceptable to suggest that all sea and swell forecasting should be done by hand, but until such time as adequate small-mesh models have been developed which take into account some or all of the additional factors involved, it is considered that some compromise should be adopted and some manual analyses utilized.

b. Shortcomings in models for coastal waters. The capability to provide working models for sea and swell forecasting in coastal waters is even more bleak. Essentially, it is a different problem which receives less attention in spite of the greater need for adequate advisories. This is of some concern since:

(1) Breaking waves are chiefly encountered in shallow waters and are the primary cause of damage to small ships and boats, occasionally resulting in loss of life.

(2) Wave heights and steepness factors are of special operational significance in coastal areas and on harbor bars where the fetch or duration of wind flow is constrained. In coastal waters a proportion of winds blow from offshore and some are channeled flows between hills and mountains.

Few national weather services are geared to deal with such specialized problems efficiently. A widespread view is held that it is unnecessary for ships to report the weather when within 50 miles of the coast, presumably because accurate weather reports are available from coastal stations. The need for weather reports is perhaps even more necessary than from the open oceans since the air and sea temperature gradients close to a coast can be extremely sharp. The fault for this illogical procedure lies in the communication networks which in most countries are insufficient to deal with the meteorological traffic from both ships of opportunity and coastal traffic. This traffic is high, and much of it is transmitted by voice which is unsuited to computer handling without conversion. National weather services have largely committed themselves to numerical techniques unsuited to voice communication, which increases yearly as the numbers on ships' crews decreases. A threat is developing that the large weather computers will be starved for quality data from the oceans in the foreseeable future.

The reason why the small ship communities, fishermen, yachtsmen, and so on express more discontent with weather forecasting services than other users is that much valuable and significant reported sea state data are never considered in computer analyses. Many seamen feel that the time and effort they put into reporting the weather from sea is largely wasted.

1.9 Need for small-mesh models. Coping with the detail necessary to produce adequate sea and swell forecasts in coastal waters requires the further development of small-mesh local numerical models. It is unjustified to assume that adequate analyses from land masses combined with the analyses from the open ocean overlap to provide sufficient analyses for coastal waters. They certainly do not, and the most urgent problem is probably to devise ways and means to improve the data inputs from coastal waters. The models need to be complemented with sub-routines which include the "twisting terms" and particularly the effects of energy feedback (both sensible and latent heat) from the oceans to the atmosphere. Furthermore, the models must include vertical motions and precipitation forecasting sub-routines. As a first requirement, there is a need for small-mesh (40 nautical miles grid-size) three parameter (surface, 500, and 300 mb level model); although it can be argued that an 850 mb model is indispensible for forecasting offshore wind flow.

1.10 Forecasts for specific operations. In dealing with specific operations, such as pipe laying on a continental shelf or landing operations on open beaches, it is desirable to operate a personalized advisory service. Seamen of experience will often arrive at the best sea and swell prediction as a result of years of experience in dealing with the problem. This is particularly so in anticipating unusual developments for a short time period ahead (six to twelve hourly predictions).

There are many reasons why seamen should resist the current trend to vest the task completely in the hands of remote weather centers. Optimum services to shipping will only result if there is mutual understanding and close cooperation between the user on the spot and the shore-side forecaster with the maximum interchange of information and opinion between them. Efforts must continue towards making the receipt and dispatch of weather messages to and from ships more efficient. Good communications are the secret of all weather services, and it applies particularly to marine advisories.

In certain circumstances, as for example when forecasting for aircraft operations on aircraft carriers, it may be necessary to establish a forecasting unit on board ship. This is only justified if backed by adequate communication channels. A good series of synoptic and prognostic charts is essential if the service on the spot is to function efficiently. Although these charts are normally available in facsimile form from national weather services, they are seldom detailed sufficiently. A ship or oil rig platform with a forecasting service must have the capability of receiving other ship reports and making observations itself to a high standard of accuracy; preferably including the capabilities to make soundings of the lower atmosphere by radiosonde and to obtain the thermal and current structure of the upper strata of the sea by bathythermographs and current meters.

An understanding of the principles involved in wave propagation is desirable, although not absolutely essential for forecasting purposes, and this involves some theoretical treatment of the subject. This is considered in Appendix A.

CHAPTER

2

OBSERVING AND MEASURING SEA AND SWELL

2.1 Observing sea and swell. Before considering the methods used for forecasting sea and swell, it is first necessary to describe the techniques employed in observing and estimating the deformation of the sea surface and to say a little about the various instruments which have been developed to make actual measurements. It will be shown later that the quantity which best defines the sea state is E, the amount of energy required to create the deformed surface. The quantity E cannot be measured directly and has to be estimated or derived from measurements of wave height, period, and length.

Marine observers need sufficient training to estimate these parameters and must first learn to distingquish between sea and swell and to make the required estimates independently. When sea and swell are moving in approximately the same direction (this is very often the case in the temperate zones), it is a difficult task requiring skill and experience. In the open ocean, particularly in the sub-tropical high pressure belts where pressure gradients are low, it is relatively easy to observe the swell and once the skill has been developed to pick out the characteristic rounded crests. It becomes much easier to distinguish them from the more confused seas created by the wind waves in higher latitudes.

2.2 Wave heights. To make a sea and swell observation, the observer should first concentrate on estimating the height of the waves. If it is possible he should position himself on a deck level so that his eye is at about the same height above the waterline as the height of the larger waves. By using the horizon and the known height of some mast, jackstaff, or stanchion he can soon make estimates of the heights of the well-defined waves. He will follow a natural inclination to ignore those which are not well formed.

Statistically, it can be shown that averaged estimates of such wave heights are approximately the mean height of the highest third of the waves in the entire wave spectrum varying from the capillary waves to the highest combination of wave amplitudes. It is the most important and stable estimate or measurement made in wave techniques and is called the ''significant'' wave height. From the significant wave height it is possible to make estimates of the total energy in the deformed surface and hence, derive other useful quantities such as the height of the highest waves likely to be encountered under any circumstances.

2.3 Wave periods. Using the second hand of a watch or a stopwatch, an observer can measure the wave period of the swell and the sea. In general, if a swell is well-defined, the period is comparatively regular and much easier to determine than that of a sea. The observer should wait for a series of well-defined wave crests to pass the ship and take the mean of the periods as best possible.

Observing the period of the seas created by the wind waves is a much more difficult matter and may require some weeks of practice before the observer develops any sense of confidence in his observations. When seas are developing into swells more than one period may be present. At this formative stage some apparently well defined periods are in effect immaturely developed swells created by winds at some distance from the ship. On many occasions it will be very difficult to pick out more than one period.When this is so, the observer should concentrate on a well-defined piece of foam and take the time for it to complete about ten oscillations. The maneuver should be undertaken at least three times and a mean period obtained from all the observations.

2.4 Wave lengths. In general, observers at sea do not estimate wave lengths since it is even more difficult to estimate accurately than the period. It is difficult to tell when the ship is actually on the crest of a wave. The wave length may be derived theoretically from a knowledge of the period (see Appendix A) and, if the latter is estimated or measured carefully, the wave length can be calculated. It is often useful for a ship to do this since swells can set up disconcerting resonant motions which lead to a serious loss of speed. Many of the swells from distant storms have a period within the range 10 to 13 seconds for which the corresponding wave lengths are approximately 500 feet and 850 feet. The lengths of many cargo and passenger vessels lie within this range also. When steaming into such swells, particularly at speed, resonance is quickly set up until the bow ultimately digs into the sea. The moment of inertia of a ship about a transverse axis is far greater than it is about a fore and aft axis and a pitch resulting from a swell will usually have greater effect of loss of power than a roll caused by a sea. This has an important economic bearing on fuel consumption.

The wave lengths corresponding to the periods of sea waves are generally much shorter and, as discussed above, are usually more difficult for an observer to estimate than the wave length of a swell. Nevertheless, for small ships, such as fishing vessels, some knowledge of the wave length is desirable not only because of the problems concerned with pitching but also because the steepness of the waves may lead to breaking. When waves break over a ship, the damage may be considerable, particularly if water gets inside the hull and can move around with a large free surface. In high latitudes, freezing spray may lead to dangerous ice accretion by adding top-weight to the superstructure.

In practice, forecasting is concerned with a combination of sea and swell and the combined result may be to cause the ship to yaw, (*i.e.,* to follow an erratic course with consequent loss of speed over a longer distance). The handling of the ship in these circumstances calls for considerable experience by the ship's captain.

The effects of waves on ships is very much an individual one, depending on the design of the ship and the loading of the vessel. It is also necessary to consider the purpose to which she is to be used. In certain cases, it will be necessary to give primary consideration to speed and fuel consumption in order to maintain schedules. In other cases, damage to cargo or comfort of passengers may be the main concern. Many ships are designed to "ride" waves and long swells; often those having considerable height will present no problems to them. In contrast, some naval vessels need to provide stable platforms for weapon systems and are designed to go through waves. Tankers fall within this category, and conditions on the deck are frequently very wet. Whatever the vessel, there are certain bands in the wave spectra with corresponding periods, heights, and wave lengths in which the vessel is difficult to handle and susceptible to damage.

Ships with a high freeboard may also suffer from a sail effect, and this also may need to be taken into account in the handling of the ship.

2.5 Measuring sea and swell with wave recorders. In recent years, considerable progress has been made toward developing reliable wave recorders for use in stationary research vessels, in moored buoys, or on stable platforms such as oil rigs. These instruments mainly rely on the measurements of vertical velocities and accelerations of a floating instrument but are sufficiently delicate to prevent their use in a moving ship, which itself sets up wave motions in its passage through the water. It is not proposed to provide details of the design and mode of operation of such instruments. It may be some time before it is possible to record sea and swell accurately on any type of moving ship with a corresponding capability to analyze wave traces with the aid of a shipborne computer. Many ships are now beings equipped with instrumentation to measure stresses and strains in rough seas, and the corresponding measurements of sea state (as opposed to estimates) would lead not only to improved ship designs and cargo stowage, but also should provide guidance to a master on ship handling in rough weather.

Figure 1 represents a typical wave trace from a wave recorder installed in a wave rider buoy. It is a visual representation of a deformed sea surface and may be used to derive the important quantity E, the energy content in the deformed surface, and from this the significant wave heights and periods.

It is possible, but often difficult, to pick out the swell as distinct from the sea in such a trace, and it may require an experienced eye to do so. Only about 16 wave lengths are illustrated in Figure 1, which roughly corresponds to 2 minutes of trace. When using a recorder of this nature to measure heights and periods of the sea, the machine should be allowed to run for at least 10 minutes to find the average time taken for 60 to 100 wave lengths. It is normally difficult to identify some of the crests and troughs exactly, and hence, it becomes necessary to average values over a fair length of trace to derive a mean.

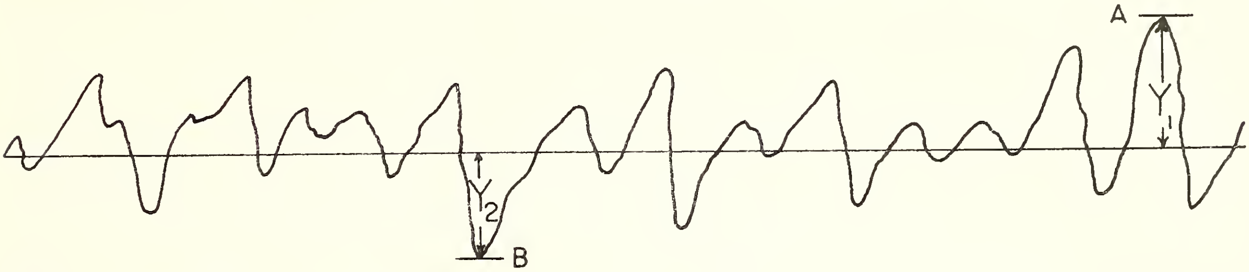


Figure 1 - Representative wave rider buoy wave trace.

In the shortened length of trace illustrated, the point A is the highest level attained at distance y_1 from the axis and point B is the lowest level attained at distance y_2.

The sum $(y_1 + y_2)$ in an entire trace taken over a minimum run of ten minutes is considered to be a measure of the maximum wave height. The highest crest and the lowest trough need not necessarily be consecutive when making this observation.

The significant wave height is approximately $\frac{2}{3}(y_1 + y_2)$.

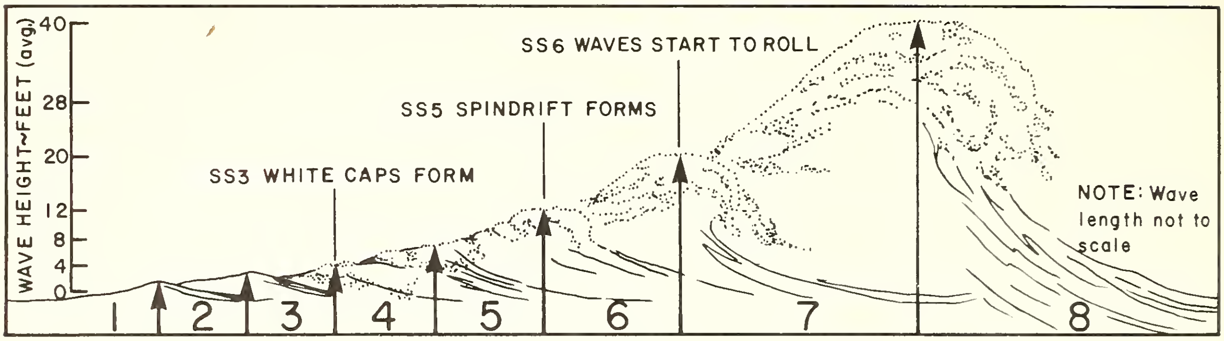
2.6 Other methods of measuring sea and swell. Various other methods, notably radar, are being used to measure heights and periods of sea and swell. Again no detail will be provided except to state that over-the-bow radars installed in ships for this purpose have had limited success and cannot at this time provide very reliable results if they are to be cost effective. Radars installed in aircraft for the purpose have had more success. The results of trials of a suitable radar in orbiting satellites will be awaited with great interest. [Preliminary analysis of radar altimeter data from the first Seasat indicates that the significant wave height can be determined to an accuracy of ± 0.5m.].

2.7 Definitions of wave heights in common use. From the practical viewpoint of the seaman, approximate linear relationships exist between the state of the sea and the wind force measured in Beaufort scale (see Table 3). These relationships are shown in Figure 2 defining sea state in categories 1 to 8 and relating these categories to the wind speed or force. It should be understood that these relationships are for general use and apply mainly to sea waves created by the local wind. Some agreed definitions of wave heights derived statistically from trace measurements are as follows:

a. The design wave (or 100 year wave). This is the height of the highest possible wave which is considered possible to occur at a certain point under the worst possible combinations of sea and swell over a very long period of time (*e.g.,* 100 years). Construction engineers need such information in order to build in necessary margins for safety when designing platforms, oil rigs, and so forth, allowing for every combination of adverse circumstances. A rough estimate of the height of a design wave can be obtained from a few samples of wave rider buoy traces. Obviously, the estimate will be better the greater the number and the longer the traces considered.

**Ed. note: Sea state descriptors used by the National Weather Service in its forecasts vary somewhat. In Alaska, these are used: slight (0-3 ft.); moderate (4-8 ft.); rough (9-13 ft.); very rough (14-19 ft.); high (20-29 ft.); very high (30-44 ft.); phenomenal (45 ft. or higher). In the rest of the U.S., these are used: smooth (0-1 ft.); light chop (1-2 ft.); chop (2-4 ft.); rough (4-8 ft.); very rough (8-12 ft.); high (12-20 ft.); very high (20 ft. or higher).*

SEA STATE with a listing of visual and tactile clues



SEA STATE DESCRIPTION

SS1	SMOOTH SEA	Ripples, no foam. Wind*: light air, 1-4 kts. Beaufort 1. Not felt on face.
SS2	SLIGHT SEA	Small wavelets, no foam. Wind*: light to gentle breeze, 4-10 kts. Beaufort 2-3. Felt on face, light flags wave.
SS3	MODERATE SEA	Large wavelets, crests begin to break. Wind*: gentle to moderate breeze, 7-15 kts. Beaufort 3-4. Light flags extended.
SS4	ROUGH SEA	Moderate waves, many white caps, some spray. Wind*: moderate to strong breeze, 14-27 kts. Beaufort 4-6. Wind whistles in rigging.
SS5	VERY ROUGH	Sea heaps up, with spindrift and foam streaks. Wind*: moderate to fresh gale, 27-40 kts. Beaufort 6-8. Walking resistance high.
SS6	HIGH SEA	Sea begins to roll, dense streaks of foam and much spray. Wind*: strong gale, 40-48 kts. Beaufort 9. Loose gear and light canvas may part.
SS7	VERY HIGH SEA	Very high waves with overhanging crests. Sea appears white as foam scuds in very dense streaks. Visibility reduced. Wind*: whole gale, 48-55 kts. Beaufort 10.
SS8	MOUNTAINOUS SEA	Very, very high rolling breaking waves. Sea covered with foam. Very poor visibility. Wind*: storm, 55-65 kts. Beaufort 11.

* Correlation between sea state and wind description is highly variable and dependent on fetch and wind duration. For seas not fully arisen, wind speeds may be much higher than indicated.

Figure 2 - Sea state with a listing of visual and tactile clues.

b. The very high waves ($H_{1/10}$). One measurement employed is to find the average height of the waves in the top tenth of the wave spectra. This quantity approximates to the maximum height observed in making an observation over a 10-minute period.

c. Significant wave height ($H_{1/3}$). The significant wave height is defined as the average of the heights of the highest third of the waves and was chosen because it was considered to be the wave height that an observer will report as being most typical of a given sea state. A comparison between measured observations and estimations by skilled observers in weather ships has shown that the agreement is close and that the defined quantity "significant wave height" is the most useful and stable one.

d. The average wave height. The average wave height is obtained by measuring the heights of all waves in the spectrum and taking the mean. Obviously, the number of low waves will predominate.

2.8 Sea and swell reports transmitted by ships at sea. Selected ships or ships of opportunity report sea and swell every six hours in the international code for weather reporting. Two groups exist in the message for this purpose. The first pertaining to the sea waves assumes that the wave direction in a sea is that of the wind and the second to the swell, which will usually come from the direction of some distant storm. Codes are employed for these specific groups, the coded figures not necessarily representing measurements. The groups which follow consecutively in a synoptic weather message are as follows:

$$\underset{\text{sea}}{3T_WT_W\,H_WH_W} \qquad \underset{\text{swell}}{D_WD_WT\;H_WH_W}$$

where $T_W\;T_W$ = period of sea (seconds),
$H_W\;H_W$ = significant height of sea or swell (coded in half-meters),
$D_W\;D_W$ = swell direction in tens of degrees (true direction from which the swell is coming);
T = period of swell (seconds).

Such paramenters have generally been estimated, but occasionally measurements are made in weather ships or research vessels using a Tucker waver meter; although it is generally not practicable to obtain readings in real time.

Sea and swell measured by buoys are usually reported in like manner, but spectral details are also available, and the means of reporting this information is discussed in Chapter 12 and Appendix C.

2.9 The quality of the data. The measurement of all environmental parameters on board a ship or a buoy presents special problems owing to the irregular movements of the vehicle. A number of empirical formulas will be quoted later based on large numbers of observations and measurements, and it is appropriate to indicate that much of the data, particularly when rough conditions prevailed at high wind speeds, may have been in considerable error.

The wave data received from buoys has at last reached the stage where it can be regarded as sufficiently accurate and reliable to be used in a statistical analysis. Several buoys have survived hurricane conditions and provided excellent records of the wave conditions throughout. However, it must be noted that in establishing relationships between wave data and wind speed, temperature, dew point, and so forth, it is equally necessary to measure these parameters with equivalent precision. Unfortunately, the wind data from buoys is not always reliable when the significant wave height exceeds 16 feet, and it is in the higher range that high quality data remains sparse. The wind is measured by an anemometer sited at 10 meters above the waterline in the upright position. When gale force winds have prevailed for several hours and sea states approach fully developed conditions, the buoys are often tight on their moorings as a result of induced surface currents and inclined to the vertical. The anemometers are then for a large part of the time below the crest level of the seas and swells and not fully exposed to the wind. Hence, wind speed is under recorded. This effect is frequently noticeable after a major storm, once the decay stage of the sea and swell has commenced. The buoy may continue to record sea and swells in excess of 20 feet but the corresponding wind speeds are low, sometimes by as much as five to ten knots.

This problem has long been known to seamen in sailing ships, for the wind is frequently taken out of the lower sails when dipping into troughs between the high swells.

The most reliable data from which to establish statistical relationships is still that collected aboard the weather ships where well-maintained reliable instruments are under the constant supervision of skilled observers.

The data collected by ships of opportunity are generally of very high quality, but it should be appreciated that the observers are often making measurements and estimates in very difficult circumstances with the ship underway. Measurements of wind speed by anemometers in ships are not very reliable since the exposure of the instrument varies with every course and speed change of the ship. In making any measurements of temperature and wind speed on board a vessel, ensuring good exposure is essential, and it is best if it can be varied according to the circumstances. On certain courses and speeds relative to the wind, hot funnel gasses can and do get carried to sensing devices mounted at fixed postions on masts and elsewhere. Similarly, the air currents affecting the instruments do on occasion pass first over hot bulkheads or decks. Competent monitoring of observations on board can largely eradicate such spurious data. It can be done automatically by increasing the number of sensors and filtering out questionable data, but this necessitates a considerable increase in costs.

There continues to be considerable pressure in some organizations to have all ships instrumented for automatic interrogation by satellite, but great technical problems have to be surmounted, and it may result in some loss in the quality of observations. The loss of data, such as visibility, cloud height, cloud type, and so forth, which can only be made by human assessments, is appreciable.

2.10 Measurements from satellites. The very rapid and spectacular advances which have been made in satellite imagery during the last decade encourage the hope that it will ultimately be possible to measure environmental parameters from outer space and transmit them directly to interested users. For some years attempts have been made to measure mean air temperatures of layers and also sea surface temperatures and some success is claimed for them. Basically, the method seeks to measure radiation accurately, but losses due to absorption depend on a considerable number of variable such as humidity, ozone layers, and carbon dioxide. Considerable progress has been made towards solving these difficut problems.

The launching of the Seasat satellites is of particular, if not crucial, importance to the maritime data collection system. The withdrawal of many of the world's weather ships from service has been influenced considerably by the acclaimed potential for the Seasat satellites, but they are not as yet proven, still less in service.*

One particular facet is the inclusion of a very high quality radar which can measure deformation of the sea surface sufficiently to deduce the significant wave height. The first lauching is scheduled for 1978 and the results will be studied with great interest by the maritime world. If successful they will have a major impact on a number of techniques used to provide sea and swell services.

2.11 Descriptions of "freak" waves. This chapter will be concluded with some descriptions by seamen of the large amplitude waves they have encountered from time to time. In 1827 Captain Dumont D'Urville, a French scientist and Naval officer in command of an expedition, reported encountering waves 80 to 100 feet high and was laughed to scorn for his exaggerations by the world's scientific community of that time. A few years later Fitzroy (later Admiral Fitzroy who issued the first national weather forecast in England in 1861) recorded a case where the wind was taken out of the sail of the *Thetis* as she "fell" into a trough between two great crests near the Bay of Biscay during a full gale. From this he estimated the height of the wave to be over 60 feet, which made the scientific community think again. The highest wave ever assessed, one with an amplitude of 112 feet, is credited to *U.S.S. Ramapo* and was encounted in the North Pacific in 1933.

**Ed. Note: A Seasat satellite was launched on 28 June 1978 by the United States, but failed after about three months of operation due to a massive short circuit in its electrical systems. Although Seasat only lasted a short time, the measurements it made proved that satellites can effectively monitor many features of the ocean environment.*

An ocean observing satellite system called NOSS (National Oceanic Satellite System) under consideration by the United States may become operational after the mid 1980s. Some of the parameters to be measured are: sea state, ocean surface wind velocity, ocean currents, sea surface temperature, and amounts of water vapor in the atmosphere.

Seamen who have experienced the impact of large waves have likened the event to striking a mine or being torpedoed, and some have considered themselves lucky to survive as the vast weight of water has descended on the upperworks. It is disturbing that some of these events have occurred with extreme suddenness, catching the crew off guard; the actual weather at the time not necessarily being phenomenally bad for that particular area.

2.12 Giant wind waves and swells. Very high waves can be generated by storms in any ocean if circumstances are right. From 22-23 October 1968, the oil drilling platform SEDCO 135F located in Queen Charlotte Sound of British Columbia, Canada experienced a dramatic increase in wave heights when the significant wave height increased from about 14 feet to over 65 feet in less than six hours! A 100 foot high wave also slammed into the drilling rig.

Waves in this instance resulted from an intense storm (with winds to over 80 knots) that was moving as fast as the waves were traveling and in the same direction. This allowed the wind to act on the same group of waves continuously, building them higher and higher, which is not the case when a stationary or slow moving storm generates waves. In the latter case, waves continuously leave the fetch area as new ones are generated at the start of the fetch. Some comments on the theoretical aspects of huge swells will be considered in Chapter 6 and Appendix A.

The longest swells in the world have almost invariably been noted in the southern oceans where the fetch is usually more than adequate to obtain full development. Such swells may well exceed one-half mile in length and have an amplitude of over 40 feet. In the open oceans they do not necessarily constitute a danger to shipping and in normal circumstances can be ridden easily by a ship. Such swells by themselves may be described as having a certain majestic grandeur, and the following graphic description of them is quoted from Commander Worsley's book, *Shackleton's Boat Journey:*

> ''Offspring of the westerly gales, the great unceasing westerly swell of the Southern Ocean rolls almost unchecked around this end of the world in the Roaring Forties and the Stormy Fifties. The highest, broadest and longest swells in the world, they race on their encircling course until they reach their birthplace again, and so reinforcing themselves sweep forward in fierce and haughty majesty . . .
>
> ''At times, rolling over their allotted ocean bed, in places four miles deep, they meet a shallow of thirty to a hundred fathoms - the Birdwood Bank, near Cape Horn, the Agulhas off the Stormy Cape, and others. Their bases retarded by the bank -their crests sweep up in furious anger at this check, until their front forms an almost perpendicular wall of green rushing water, that smashes on a ship's deck, flattening steel bulwarks, snapping two-inch steel stanchions, and crushing deckhouses and boats like egg shells. These blue water hills in a very heavy gale move as fast as twenty-five statute miles an hour, but striking the banks, the madly leaping crests falling over and onward, probably attain a momentary speed of fifty miles or more. The impact of hundreds of tons of solid water at this speed can only fairly be imagined. Even on deeper banks they may be seen 'topping up,' for the disturbance of these huge rollers extends down a thousand feet at times . . .''

2.13 Killer waves. A number of ships of sound construction have disappeared without trace and although many of such losses may have been due to running onto uncharted rocks or mines (a cause which can seldom be entirely ruled out as a possibility) it is more probable that many of them have been vitally damaged by a huge wave which has displaced cargo. Some trawlers and fishing vessels may have been broached (rolled over) or pitch-polled (upended) by a sudden impact with an almost vertical wall of water, and, if this explanation is correct, such waves have rightly earned the description of ''killer'' waves.

An early account of a ''freak'' wave is taken from the diary of events of Sir Ernest Shackleton describing his epic voyage of survival on the open boat journey from Elephant Island to South Georgia in 1916:

> "At midnight I was at the tiller and suddenly noticed a line of clear sky between the south and southwest. I called to the other men that the sky was clearing, and then a moment later I realized that what I had seen was not a rift in the clouds but the white crest of an enormous wave. During twenty-six years' experience of the ocean in all its moods I had not encountered a wave so gigantic. It was a mighty upheaval of the ocean, a thing quite apart from the big whitecapped seas that had been our tireless enemies for many days. I shouted, 'For God's sake, hold on! It's got us!' Then came a moment of suspense that seemed drawn out into hours. White surged the foam of the breaking surf. We were in a seething chaos of tortured water; but somehow the boat lived through it, half-full of water, sagging to the dead weight and shuddering under the blow. We baled with the energy of men fighting for life, flinging the water over the sides with every receptacle that came to our hands, and after ten minutes of uncertainty we felt the boat renew her life beneath us. She floated again and ceased to lurch drunkenly as though dazed by the attack of the sea. Earnestly we hoped that never again would we encounter such a wave."

Commander F.A. Worsley, D.S.O. R.N.R., one of Shackleton's companions on that voyage, described the event in similar fashion in his book, *Shackleton's Boat Journey,* and had an interesting theory as to its cause:

> ". . . The wave that had struck us was so sudden and enormous that I have since come to the conclusion that it may have been caused by the capsizing of some great iceberg unseen and unheard by us in the darkness and the heavy gale."

Elsewhere in the account Worsley remarked that no ice was seen throughout the voyage. A capsizing iceberg is therefore an unlikly cause of the wave. Icebergs which are in danger of capsizing or overturning are usually surrounded by readily visible lumps of ice called "bergy-bits." Elsewhere in the account is is stated that "there was a heavy cross sea running," which suggests that the wind waves were largely opposed to the swell so that there was a marked angular difference between the two; this would be a more likely cause of the event.

2.14 "Holes" in the ocean. In some instances, ship masters have reported falling into "holes" in the ocean when the vessel has descended into the trough between two waves at an angle of 30° to impact on a wall of water at the bottom so that a solid wall of green water comes over the bow, crashing down on the deck, smashing everything in its path. It is described very vividly in this report by Commander I.R. Johnston, R.N. (Retired):

> "When I was serving on the cruiser *Birmingham* during the Second World War we had a similar experience between Durban and East London one night which I recall the more vividly for being on watch at the time. We were about 100 miles south-southeast of Durban on our way to Cape Town, steaming fast but quite comfortable into a moderate sea and swell when suddenly we hit the 'hole' and went down like a plummet into the next sea which came green over A and B turrets and broke over our open bridge. I was knocked violently off my feet, only to recover and find myself wading around in two feet of water at a height of 60 feet above normal sea level.
>
> The ship was so jarred by the impact that many of the watch below thought we had been torpedoed and went to emergency stations. The Captain immediately reduced speed but the precaution proved unnecessary as the moderate conditions returned as before and no further 'holes' appeared."

A Sea-Land cargo ship enroute from Seattle to Alaska reported severe damage as a result of encountering such a "hole" on 20 September 1976. The master and crew did not consider the weather phenomenally bad and

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Ed. note: A fascinating account of giant waves and their effects on mariners is in an illustrated article by Peter Britton (no relation to Graham Britton) in the February 1978 issue of **Smithsonian** *entitled "Nightmare Waves Are All Too Real to Deepwater Sailors." One interesting point was that waves up to almost 200 feet high are possible in the Gulf of Alaska under proper storm conditions!*

were in no sense aware on any particular danger. The ship breasted a fairly large wave and plunged down into a deep trough, impacting heavily on the following wave which came green over the bow to smash the containers on the forward deck. The winds were only of moderate gale force, and the synoptic charts for the day showed no evidence of an intense storm.

For further information and advice on observing sea and swell from a moving ship, refer to a book by Vaughan Cornish, *Ocean Waves and Kindred Geophysical Phenomena* (Cambridge University Press, 1934). Cornish spent many years of his life carefully observing sea and swell in all oceans of the world and from exposed coasts. He also studied the movements of sand waves on shores and deserts and of snow in arctic regions. His collection of observations and descriptions of wave behavior are perhaps unique and it will provide a reader with an understanding of wave behavior which cannot be derived from theoretical treatment.

CHAPTER

3

THE STRUCTURE OF THE ATMOSPHERE OVERLYING THE SEA SURFACE

3.1 Introduction. The atmosphere overlying the sea surface is often stratified. The degree of stratification which exists in the first 500 meters in the atmosphere and in the upper levels of the oceans to a depth of 50 meters has an important bearing on sea and swell generation. A forecaster needs some understanding of the causes and behavior of low-level inversions in both media. The two are generally closely associated phenomena, stratification in the upper levels of the ocean occurring at the same time as stratification in the lower atmosphere and vice versa. Similarly, when the atmosphere overlying the sea surface is convective (generally when the air temperature is lower than the sea surface temperature), the upper levels of the ocean tend to be convective also. This is perhaps obvious since the air overlying warm seas will be warmed by contact and tends to rise. Similarly overflowing cold air tends to cool the sea surface thereby creating a colder and denser contact layer which ultimately sinks. Although convective motions are normally discontinuous processes, the tendency will be for them to occur simultaneously in both media.

The principle has an important bearing on the drag coefficient, a measure of the degree of ''bite'' which an air mass can exercise on the water surface. Observations of the behavior of smoke or fog illustrate this. Dye can be used to show similar behavior in the water.

3.2 Stratification in the atmosphere. Over land, inversions may be observed as radiational fogs on cold nights. The land radiates heat into space and in consequence the lowest layers of air become colder and denser; finally, the condensed moisture particles in the layers are a visual indicator of the inversion. Inversions are fundamentally density discontinuities with the lighter layer of air overlying the denser one; the line of separation being frequently sharp. The density discontinuity may be due partly to moisture content, although generally the temperature difference is the more important factor. Similarly, in the sea, layers form as a result of different water compositon -particularly the salinity- and this can be more important than temperature in determining the density difference.

The density of water vapor is less than that of dry air, and in consequence a parcel of humid air will be lighter than a corresponding parcel of dry air at the same temperature and pressure. Since the air in immediate contact with the sea is theoretically at or very close to saturation point, there is a natural tendency for some instability in the lowest levels, leading to some erosion of the surface duct (a shallow, nearly horizontal layer of air next to the ocean having a marked vertical temperature and moisture gradient).

Smoke rising from a ship's funnel is often arrested at the inversion or velocity shear just above the top of the masts and is trapped at this level. Satellite imagery sometimes reveal these smoke plumes extending over several hundreds of miles. They provide a good indication of the near surface wind speed and direction at the level where the smoke is trapped. This phenomenon is usually associated with a marked high pressure cell over the ocean in which considerable subsidence is taking place.

Inversions are very often present over the sea surface, particularly in spring and early summer. Evaporation is taking place from the water surface at all times, and when the atmosphere is stable and the wind is less than

12 knots, most of the evaporated water is contained in a low-lying surface duct. The tendency for a duct to occur is probably present at all times even at wind speeds up to gale force. The duct seldom extends to more than 40 meters from the surface. When the lower atmosphere is near saturation level, the inversion becomes readily apparent to the naked eye in the form of a surface haze. If the air ever becomes completely saturated or supersaturated, sea fog forms. Such ducts are responsible for the anomalous propagation of radar beams by internal reflection of the radio waves.

As seamen know well, the height of a sea fog seldom extends much higher than the tops of masts of ships. In the days of sail a man was usually posted in the crow's nest so that he might observe the masts of other ships protruding above the fog banks. Similarly, it is often possible to see further in the lowest meter immediately above the water level than from higher up at deck level. This occurs when the fog is beginning to dissipate and is probably brought about by the advection of warm water driven as a shallow layer by the wind to cover the colder water below. With such warm water advection the fog first tends to disperse from the layer adjacent to the sea surface, dispersion slowly extending upwards. As the wind force increases and brings in more warm water, turbulence increases in the atmosphere and the fog "lifts" away from the surface. The fog finally degenerates into banks of low stratus.

3.3 Convection in the lower atmosphere - arctic sea smoke. With a sea surface much warmer than the atmosphere, the air in contact tends to rise in convective columns. This may result in a special type of fog encountered in high latitudes known as arctic sea smoke. This phenomenon is chiefly observed when very cold dry air flows over the sea from off a frozen land surface. The sea surface, although near the freezing point, is several degrees warmer than the air. The rising air parcels acquire some moisture as a result of evaporation and, as they rise, condensation occurs though mixing with the very cold air mass environment. To an observer it appears that the sea surface is smouldering, the isolated rising turrets of water droplets or ice crystals looking like smoke.

The effect is frequently observed with katabatic wind flow down deep Norwegian fjords in winter, and the rising columns of "smoke" are occasionally noted to heights in excess of 1,000 feet. Generally, however, arctic sea smoke is a low level feature and may be an indicator of circumstances which could prove hazardous to shipping. Near the ice edge such circumstances aid the process of ice acretion on superstructures. Ice acretion is normally attributable to freezing spray but it is also partly due to supercooled clouds. Superstructure icing may occur extremely rapidly and quickly cause ships to become unstable and overturn.

3.4 Smoke trails in a stratiform atmosphere. Inversions and wind shears may occur in cloud-free atmospheres and specifically in the lowest layers over the sea, even when no fog or haze is present. The existence of such clear-air stratification can be revealed to the eye by meteorological smoke rockets.

The rockets are "modified very lights" such as are fired by ships as distress signals. They can reach a vertical height of about 1,000 feet where they eject a capsule which burns to emit a vivid orange smoke as it falls to surface level. The appearance is given of drawing a vertical line downwards through the atmosphere. As the differing wind currents take effect on the smoke, the trail becomes distorted thereby indicating any shearing at a density discontinuity. The trails can be monitored from a ship with two cameras, one positioned at each end of the ship. By photogrammetry it is possible to compute wind velocities at various heights.

Examples of such rocket firings in stratiform conditions are shown in Plate 1, Sequences *a, b, c,* and *d.* The photographs of the trails were taken at five second intervals, the timing being measured from the moment the capsules struck the sea surface. The four Sequences in Plate 1 are typically of stable atmospheric conditions.

In Sequence *a,* some low level stratus can be seen in the background, the remnants of a fog bank which has largely "burned off" in the morning sun. It is seen that a calm virtually prevails at sea surface, although there is an appreciable wind at the height of 40 meters. The sequence has further interesting detail since it reveals that an overturning process is taking place near the top of the duct. The behavior of the smoke indicated the existence of an internal wave moving along the discontinuity. Internal waves occur whenever the layered structure is in the process of breaking down by convective motion and is the mechanism whereby moisture is transferred vertically between layers in the atmosphere.

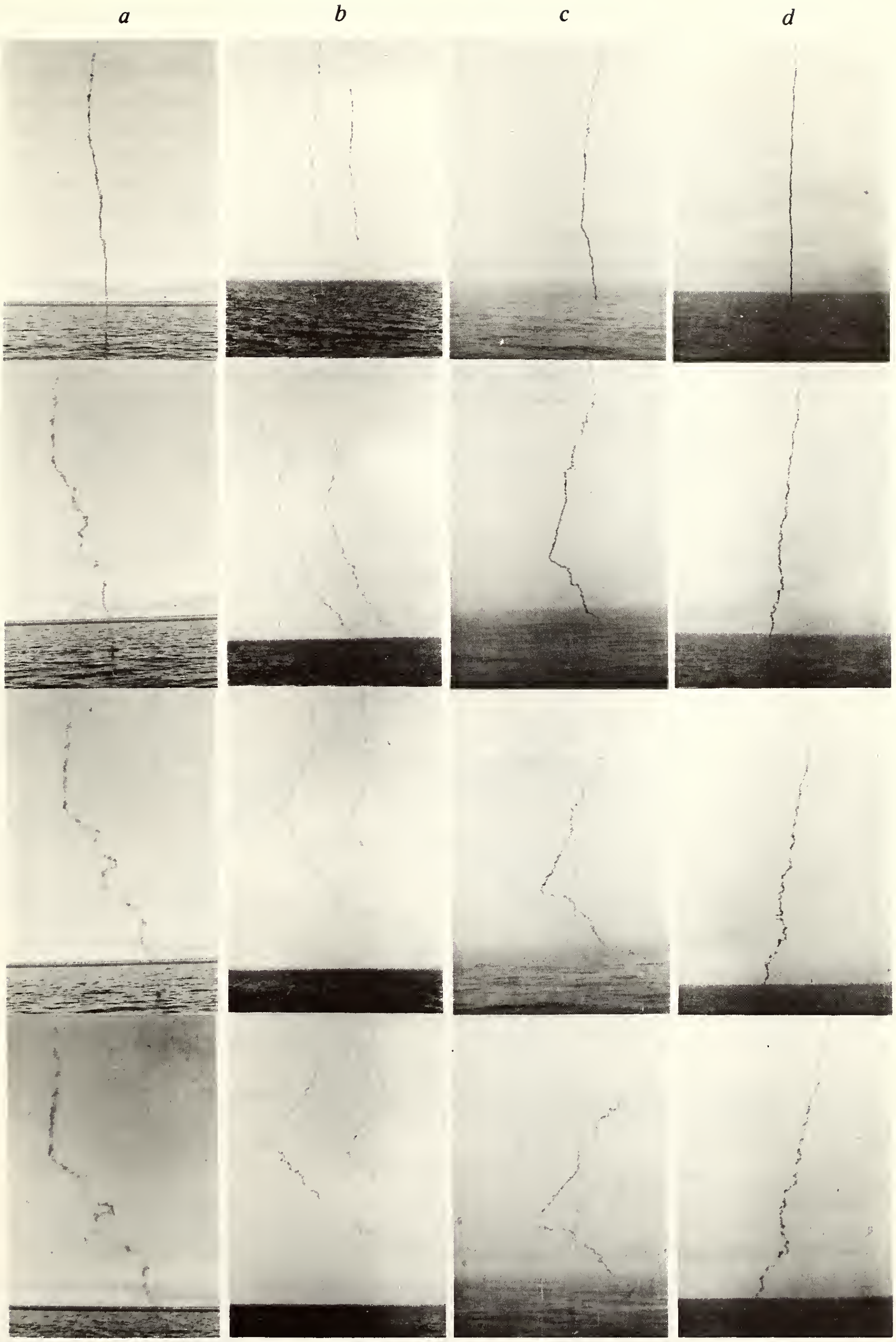

Plate 1 - Smoke trails in stratiform situations.

In this case, thick sea fog had been present in the early morning when a low level radiosonde ascent was made. The details of this ascent are shown in the plotted graphs of Figure 3. The following quantities are plotted against pressure at one millibar intervals on the left with equivalent heights in one meter intervals on the right:

(1) Virtual potential temperature, Θ_V
(2) Potential temperature, Θ
(3) Temperature, T
(4) Wet bulb temperature, T_W
(5) Wet bulb potential temperature, Θ_W
(6) Dew point temperature, T_D
(7) Specific humidity, which is a measure of density, W

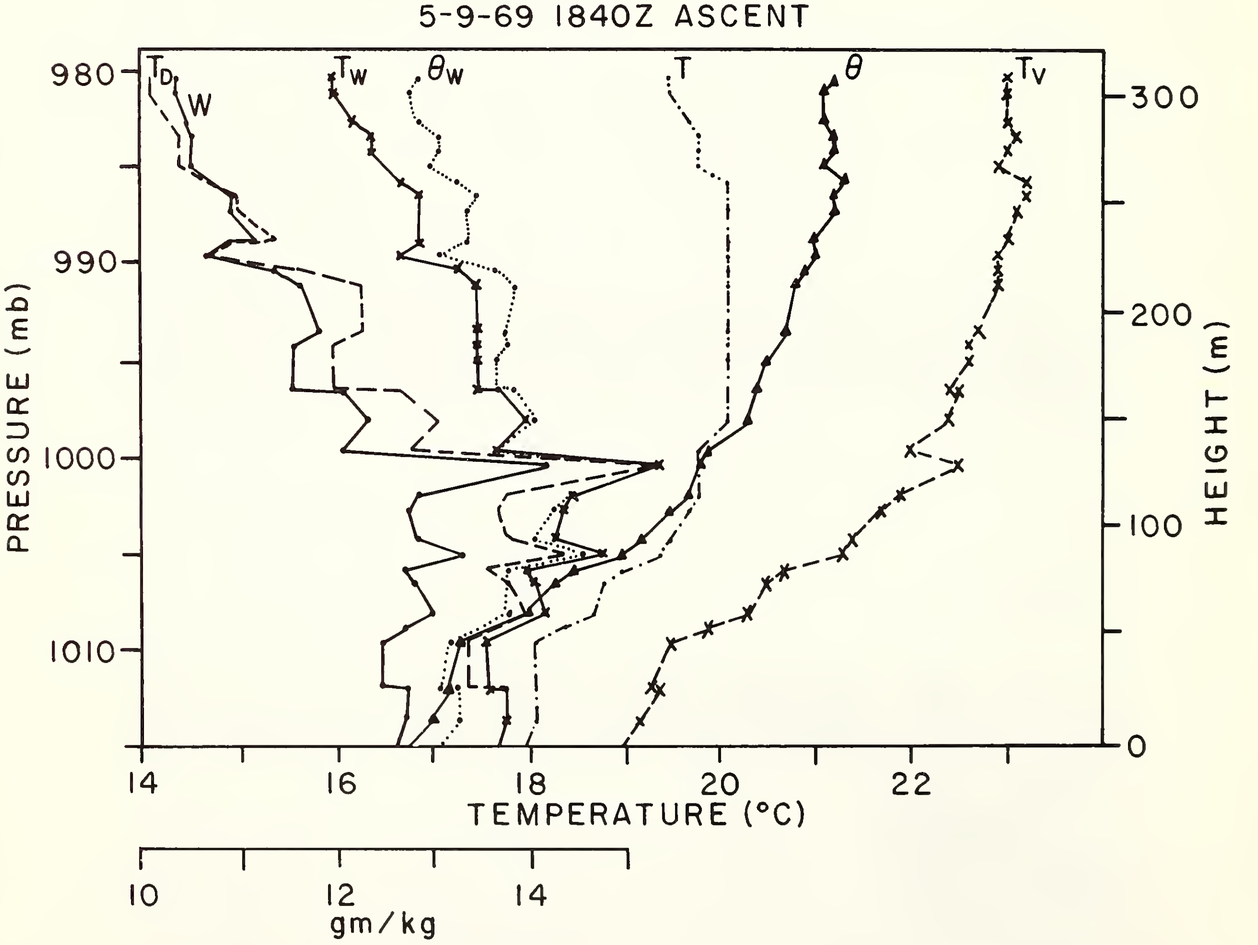

Figure 3 - Low level radiosonde plots for 5 September 1969.

The reasons for plotting all seven of these quantities will not be discussed, and it will only be stated that each serves a separate purpose when considering stability. The discontinuities at 40 meters are more readily apparent in the graphs of the parameters, 4, 5, 6, and 7 (all of which involve moisture content) than they are in the graphs of parameters 1, 2, and 3 which concern temperature alone.

Sequences *b* and *c* in Plate 1 show the development of spectacular "jets" at a height of approximately 35 meters. In Sequence *b,* the rocket ejected two capsules which fell approximately 50 meters apart. Sequence *b* was observed about 20 miles from land in the Strait of Gibraltar and Sequence *c* was observed over 100 miles from the nearest land. The atmosphere was very stable on both occasions. Photographs of such trails are difficult to reproduce since the jets occur only in conditions close to fog formation, and some haze is invariably present limiting visibility to two to three miles. *The remarkable feature is that considerable shear is occurring within the atmosphere at approximately the top of the humidity duct.* As a result there is virtually no "bite" or sea-generating effect. Simultaneous measurements of temperature and humidity made by a low-level radiosonde showed that the shear occurs at the same level as the velocity discontinuity. In such circumstances, the normal relationships between the geostrophic wind (a term which will be explained in more detail in Chapter 5) and the effective wind at sea level is completely changed. It would be true to say that in such circumstances geostrophic winds derived from a surface pressure synoptic chart would not give realistic sea and swell values. Figure 4 shows the water temperature profile for the same day as the radiosonde plot in Figure 3.

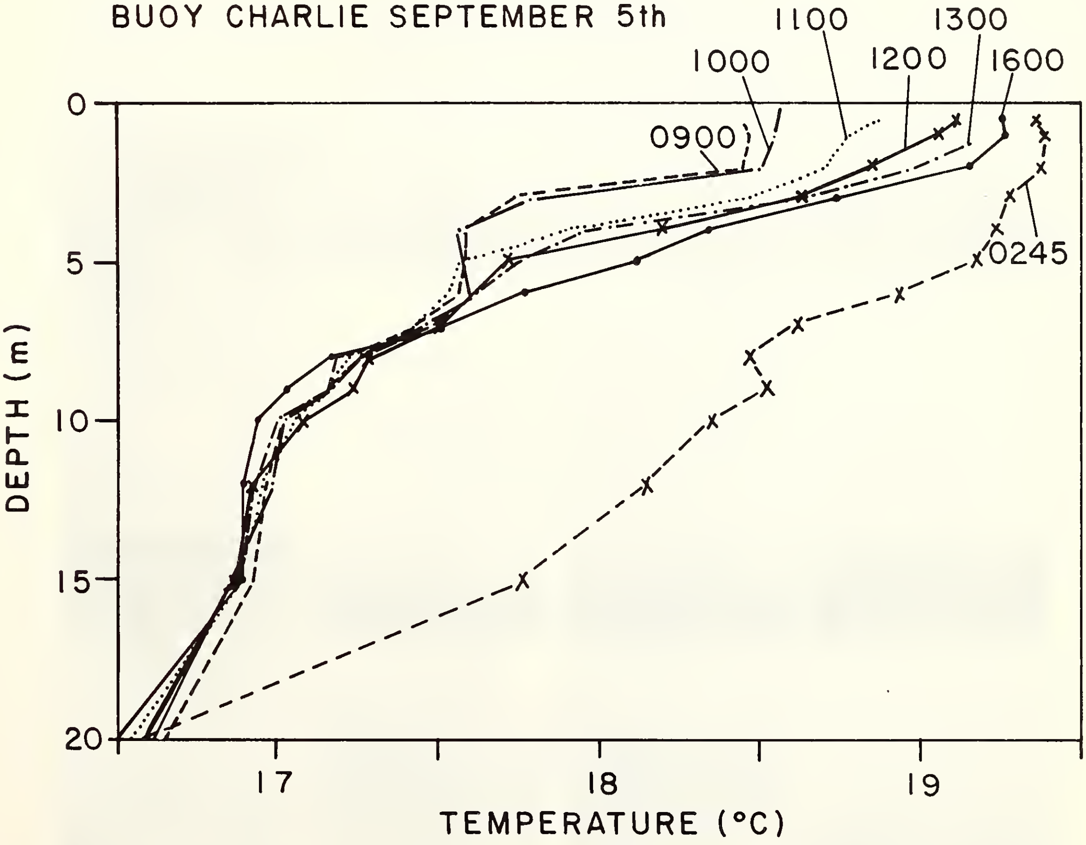

Figure 4 - Shallow depth temperature profiles for 5 September 1969.

3.5 Smoke trails in a convective atmosphere. Convection in the atmosphere can be illustrated similarly by the behavior of smoke traces. Plate 2, Sequences *e, f, g,* and *h* show rocket traces fired in unstable conditions observed when the sea temperature was higher than the air temperature. Cumulus clouds indicative of an unstable atmosphere are present in the background of each sequence. It is seen that the smoke in the trail tends

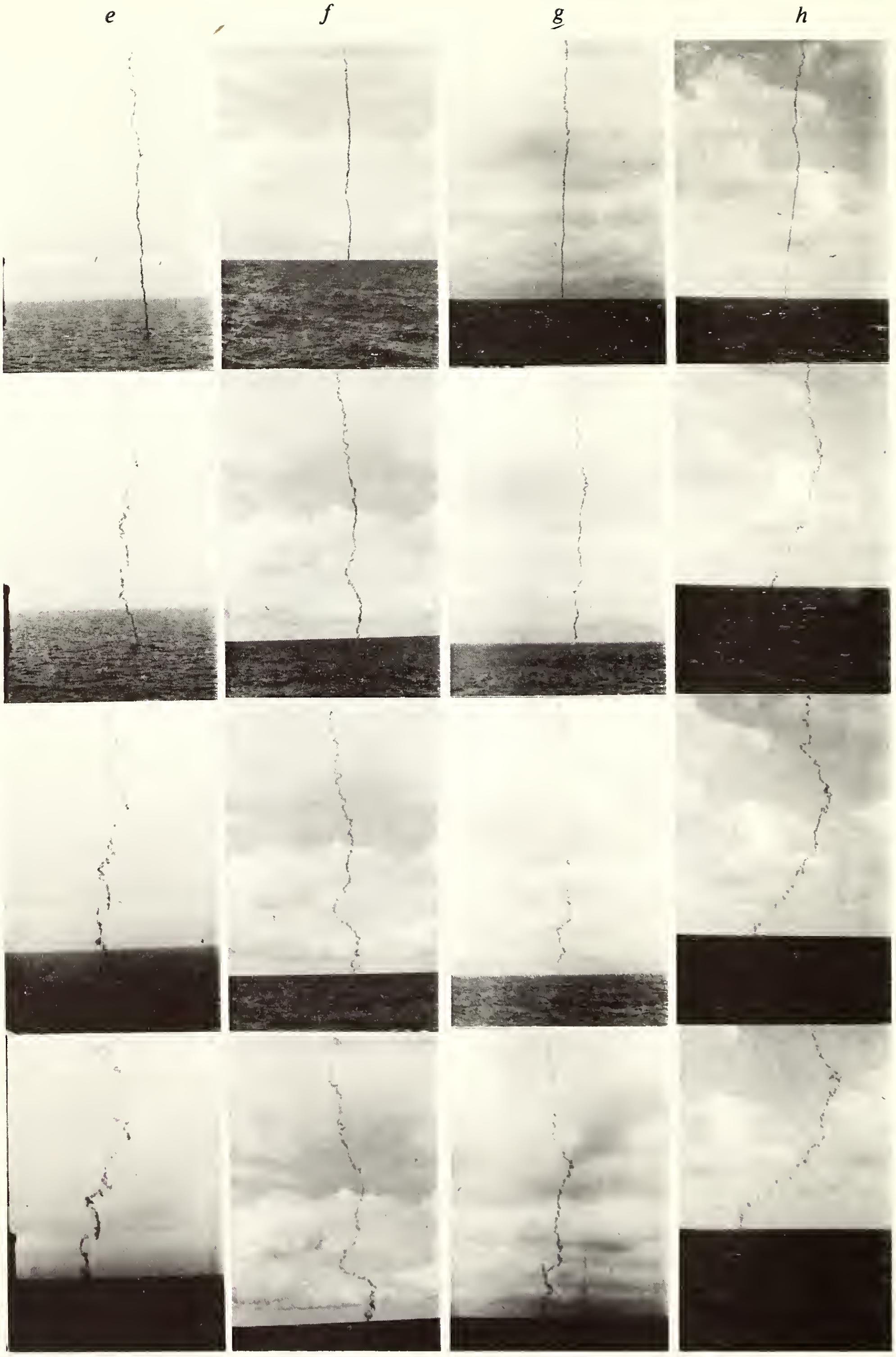

Plate 2 - Smoke trails in convective situations.

to form loops or smoke rings. The vertical alignment of the trace is better preserved. When dealing with the stratiform atmosphere, discontinuities tended to break the trails, but here the velocity change is more in conformity with the theoretical logarithmic change of velocity with height. However, the trail often breaks up into a number of disconnected loops caused by overturning processes. Corresponding temperature and humidity profiles versus pressure (or height) are shown plotted in Figure 5.

It will be seen from Figure 5 that although we are dealing with an unstable atmosphere, there is still some tendency to maintain the surface humidity duct. Thus, in Sequence *e*, some evidence of a humidity discontinuity is seen at a height of about 30 meters. In convective circumstances, the air is generally making good frictional contact with the sea surface to generate waves.

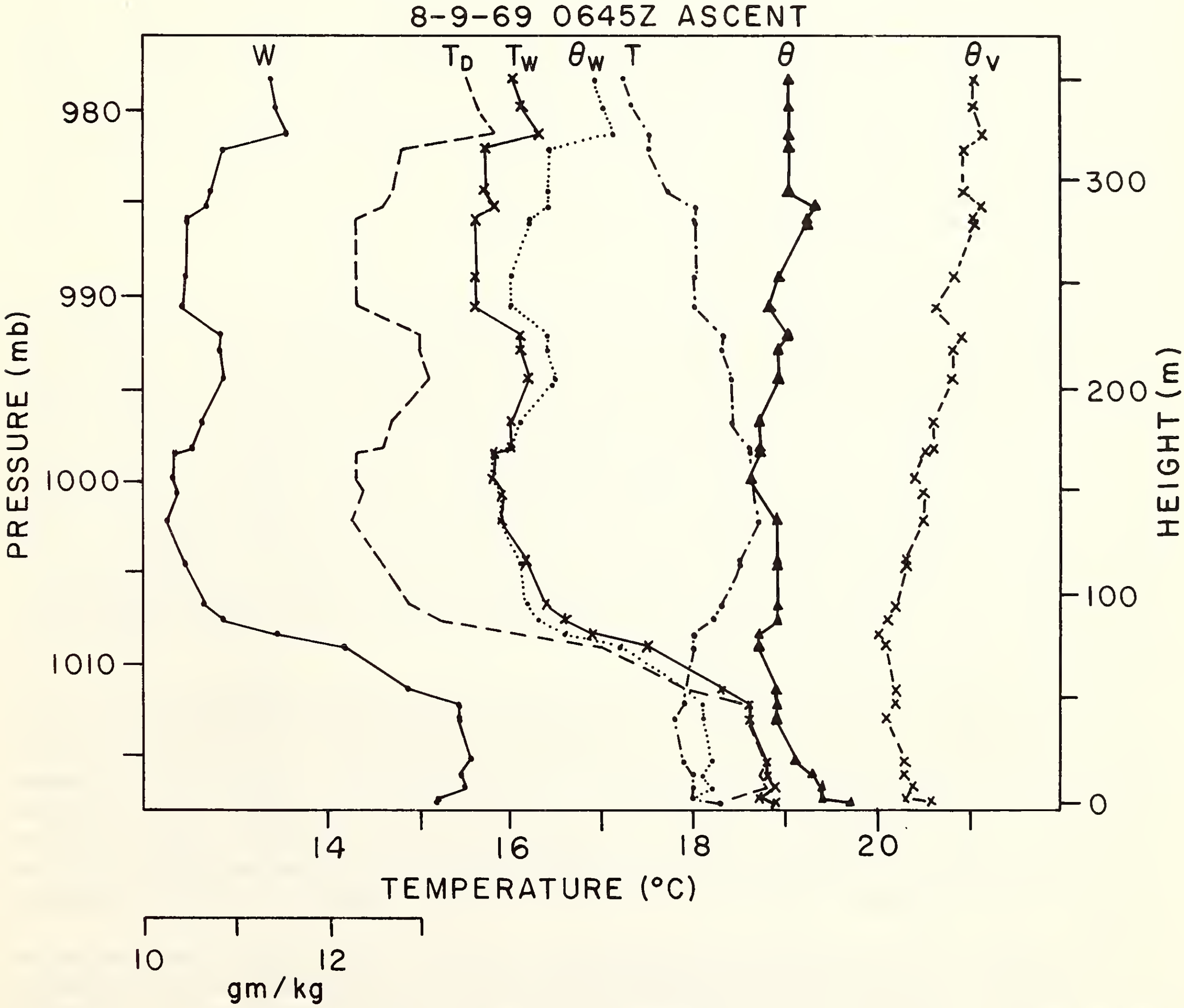

Figure 5 - Low level radiosonde plots (unstable atmosphere).

3.6 The density structure in the upper layers of the sea. The sea and atmosphere show considerable similarity, and stratified features exist in the upper layers of the ocean when the atmosphere is similarly stratified. In the sea, the existence of ducts or "sheets" can be demonstrated by the use of illuminating flourescent dye, which in effect creates artificial "clouds" that may be photographed with underwater cameras. In summer, heat is accumulated in the upper levels of the ocean to form thermoclines, the corresponding features to inversions in the atmosphere. The layers are generally the result of differential heating; although occasionally they form as a result of density differences as for example when fresh water flows out from a river mouth over denser sea water. In the tropics, layers may be formed as a result of heavy rainfall. Such density layers are called haloclines as distinct from thermoclines. But whether dealing with thermoclines or haloclines, the discontinuity indicates layers of different density having different velocity regimes on either side of the interface. The discontinuity or shear is often extremely sharp. This can be illustrated in similar fashion by dropping a particle of flourescent dye in the water and photographing the progress of the trace.

As the particle of dye falls freely in the water, it tends to draw a vertical trace similar to the smoke trail in the atmosphere. As it passes through any sheet or discontinuity, the dye indicates a change of flow and the vertical line is disturbed. If dye is injected into the water close to such a discontinuity, the dye is concentrated in the sheet by convergence and a bright horizontal line results. Profiles of temperature (and salinity) versus depth can be obtained with a temperature/salinity bridge, and these show similar characteristics to the low level radiosonde profiles of the lower atmosphere. The profiles (see Figure 4) show marked discontinuities at depths of two to three meters and were taken on the same day and at about the same time as the smoke trails shown in Plate 1, Sequence *a*.

As we shall see, the stability characteristics of the lower atmosphere and upper ocean have an important bearing on sea and swell generation at all times.

3.7 Surface currents generated by wind stress. Surface water velocities of appreciable speed (in excess of three knots) can be generated by wind stress in highly stratified seas. The onset of a 40 knot mistral following a calm summer period in the Mediterranean suggests that surface currents approaching five knots may have been generated. Tide gauge measurements in the semi-closed seas such as the North Sea and the Adriatic indicate that the surface water in the upper-most layer is displaced over long distances to pile up on downwind coasts. The surface of the sea takes on a slight inclination as a result of such stress. The displacement of surface water by the wind stress depends on the degree of shear which takes place at density discontinuities such as described above. The upper levels can become highly stratified in the summer months following periods of calm and clear skies, the first density discontinuity at a depth of a few feet being very sharp. A wind stress applied to the sea surface in such circumstances causes the top layer to move independently of the water mass below. The momentum transfer from the atmosphere is largely applied only to this top layer and results in its acquiring a relatively high velocity. Obviously much will depend on the density difference across the layer, and the greater this difference, the more marked the shear effect and gliding process. It is usually only a feature of comparatively short duration limited to a few hours.

As the water surface becomes disturbed by the wave formation, increased wind mixing takes place as the subsurface discontinuities are ruptured. As the transient thermoclines are driven downwards, momentum transfer applies to a greater mass of water and the speed of the surface layer decreases. But such top layer movement of the water can have a profound effect on the steepness of the waves generated by the wind in the early stages of sea state development, particularly when the wind flow is opposed to the movement of the water. The effect is most likely to be encountered in the fall before the erosion of the seasonal thermocline. Small ships in the Mediterranean have a particular fear of the immediate effects of the onset of a mistral and rush for port at the first signs of onset. Similarly, katabatic winds may create "walls" of water in the fjords of Alaska and Norway.

Unfortunately, very few measurements of actual velocities of surface flow exist. There are many reasons for this, the most important being that it is a particularly difficult matter to place current meters near the sea surface and get them to function accurately. Drogues may be used for making such measurements, but they are difficult to monitor and the deduced velocities are open to question. Recent research work using over-the-horizon radars tends to confirm the view that surface generated currents by wind stress applied to highly stratified seas may be considerable and perhaps exceed five knots.

An example of how a warm water layer was driven over a considerable distance by the wind is quoted in il-

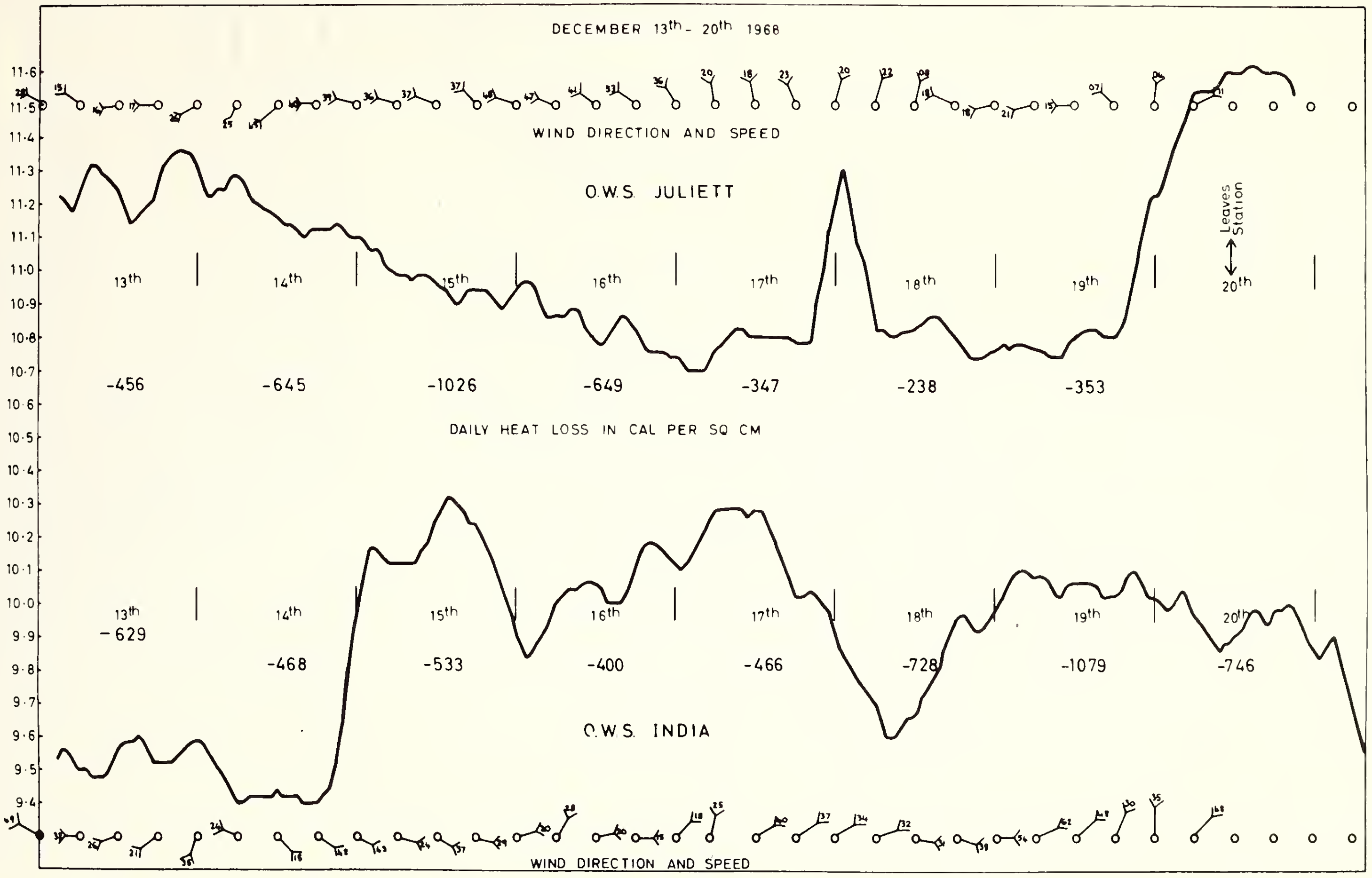

Figure 6 - Variation in sea surface temperature at OWS JULIET and OWS INDIA.

lustration. Sea surface temperature graphs at OWS INDIA (59° N 20°W) and OWS JULIET (52.5°N 20°W) are shown (Figure 6) for a five-day period during a winter gale and attention is drawn to a sudden rise in sea surface temperature of 0.8°C at 2200, 14 December 1968 at OWS INDIA. This occurred some 15 hours after the reversal of the wind direction at the ship from west to east consequent upon the passage of an intense depression in which the winds approached hurricane force.

Heat budget computations for both weather ships were carried out hour by hour throughout the five-day period and showed consistently large losses of energy by the sea. The daily losses in calories per square centimeter are shown for both vessels in Figure 6 and all are abnormally high. Since no single hourly computation showed a positive energy increase from the ocean, it was to be expected that the sea surface temperature would have fallen since energy was being rapidly taken from the sea and transferred to the atmosphere. How can such heat budget data be reconciled with a marked rise in the sea surface temperature at OWS INDIA? It could only happen if there was some warm water advection.

Sea surface temperature reports by ships over a wide surrounding area were examined carefully but showed no evidence of local warm water patches which might account for such a rise. Two days previous to the event, two weather ships going to and from station had crossed the area in question taking hourly sea surface temperatures which gave no indication of warm water patches. These were unlikely to occur in any event in mid-December. If in fact surface water was transported, it had to come from the south or south-east and over a distance of at least 120 miles to account for the rise. Furthermore, it happened in less than 24 hours, consistent with a speed of five knots or more. Similar examples of this nature are coming to light, many of them supported by bathythermograph observations showing how shallow layers of warm water are readily advected by the wind over cold sea surface areas. Attention is drawn to similar conclusions reached by gridding sea surface temperature maps. This technique is described in Chapter 6.

3.8 The application to sea and swell forecasting. To date, very little account has been taken in sea and swell forecasting of the effect of surface generated currents due to wind stress on stratiform waters. Some of the worst conditions experienced at sea follow a swift reversal of a wind direction, and as an illustration, reference is made to the loss of the ship *Edmund Fitzgerald* on Lake Superior on 10 November 1975. The 729 foot cargo ship sank after reporting that she was in a severe storm and a hatch cover had been torn off. She was also very close to a lee shore and had little room to maneuver. There has been a long history of similar events at this time of the year on Lake Superior and many shipping losses have occurred very suddenly. Local seamen have called it "the curse of the eleventh month." Why should such circumstances be more likely to occur in November than in any other month? The main reason is that the temperature changes in air masses involved are often extreme and are enhanced because the water has not entirely lost its stratiform nature from previous summer heating.

It is advantageous to record the basic facts and indicate how the combination of circumstances contributed towards the final tragedy.

(1) On 9 November 1975, a deep depression developed over central North America and moved north-northeastwards towards the Great Lakes with the center passing over the eastern end of Lake Superior into Canada in a very predictable manner. The prognostic charts predicted the movement well, and the track followed by the storm over 36 hours was exactly as expected.

(2) The winds ahead of the depression were blowing from the east-southeast, and between 0000 GMT and 0900 GMT on 10 November they were probably approaching gale force over the exposed waters of the lake. The air mass temperature averaged 10°C or more.

(3) This wind flow was sufficient to set up some surface current set towards the west along the major axis of the lake, although no actual speeds are available to quote.

(4) As the depression moved into Canada, already in the first stages of winter, the wind backed right round through 180° within the space of six hours. The warm air mass was quickly replaced by a dense cold air mass flow having sub-zero temperature. It blew in the opposite direction straight down the major axis of the lake at full gale force exercising maximum bite on the water surface as it did so.

(5) The length of fetch for this air mass exceeded 200 miles, which was more than sufficient to raise waves

of high amplitude and short wave length in minimal time. With wind and water in opposition, everything combined to make the steepness of the waves at the southern end of the lake extreme and potentially very dangerous to any vessel. Any attempt to turn a vessel in these circumstances to put her head into the wind or to avoid being driven onto a lee shore would have caused dangerous rolling motions.

CHAPTER

4

THE EFFECTS OF VARIATIONS IN AIR AND WATER DENSITY ON SEA AND SWELL GENERATION

4.1 Introduction. It was demonstrated in Chapter 3 that a cushion of air of high relative humidity is normally present overlying the sea surface to a height of approximately 30 meters, particularly when the overflowing air mass is stable. The air in actual contact with the water surface may be assumed to be saturated and have a density ϱs which may be determined directly from the sea surface temperature.

Let us assume that the air mass overflowing the water surface has a density ϱa. If the conditions are very stable, ϱa is less than ϱs, and some degree of shearing takes place within the atmosphere itself at interfaces between layers of different density. In extreme cases little or no contact is made between the air mass and the water surface, and the geostrophic wind speed bears little or no relationship to the effective wind speed which generates waves. Such conditions apply mainly at low wind speeds, but even at higher wind speeds the sea raising forces are considerably reduced whenever the atmosphere is very stable.

When ϱa is greater than ϱs, the cushion of humid air overlying the sea surface is being constantly eroded by convective motions, and it is logical to assume that the greater the difference between ϱa and ϱs the greater the degree of bite which the wind will exercise to generate sea and swell. Although the eddy motions are complex and many factors come into the equations, some measure of the speed with which seas are raised by the wind can be obtained from consideration of the factor (ϱa-ϱs).

It follows that in the sea state forecasting there will generally be the need to consider the stability of the overlying atmosphere and in particular to distinguish between stable and unstable conditons.

Stable conditions. When ϱa is less than or equal to ϱs, the energy transferred from atmosphere to ocean will be mainly kinetic energy as a result of friction between air and sea. It will only be at higher wind speeds after a marked deformation of sea surface has developed that momentum becomes an important factor. The analogy might be made between planing a piece of wood with the grain, the tool sliding easily over the surface with even drag. Such cases are by far the most common ones to consider, and it is to these cases that diagrams concerning wave heights and periods and constraints of fetch and duration will normally apply.

Unstable conditions. In this case, ϱa will be greater than ϱs. Some part, and occasionally a large part, of the energy is transferred from atmosphere to ocean by momentum as a result of the air mass impacting on the sea surface. The analogy is made here of planing a piece of wood against the grain, some degree of jar resulting from the tool biting into the surface of the wood with the resulting surface becoming rougher instead of smoother. Marked instability in the atmosphere is usually experienced in the fall and in winter. The diagrams concerning wave heights and periods with the constraints of fetch and duration need considerable modification in these cases, and, in the extreme, they are in gross error. Maximum height of waves can be raised in a very short time or in short distances under such circumstances.

4.2 Energy and momentum transfer. Sea and swell generation is essentially concerned with the transfer of energy from the atmosphere to the ocean and both of these quantities are directly proportional to mass. Hence, in transfer processes, the density of both the air and the water are involved. Other things being equal, the same wind force at the same temperature and pressure will raise higher waves in less time in fresh water than in salt water—a point to be born in mind when dealing with practical problems, such as the case discussed in Chapter 3 concerning sea state conditions over Lake Superior.

Similarly, if the air pressure is high and the temperature low, the density of the air mass is high and thus the impacting force of the wind on the water is increased and will raise sea and swell quicker.

When an air mass has been flowing over a water surface in a constant direction for an appreciable length of time, a sea surface current is induced. At the next frontal passage, particularly if it be a cold front accompanied by a marked wind veer, the result is some generation of cross-seas which will produce embarrassing wave combinations, particularly to small ships. Some measure of the likely effect can be obtained from values of ϱ_{a1}-ϱ_{a2} where ϱ_{a1} and ϱ_{a2} are the respective densities of the air masses on either side of the front.

In the ensuing paragraphs, air density variations will be discussed in more detail at surface level, and some examples will be given of how such considerations have practical importance.

4.3 The variations of air density with temperature. The air is a mixture of gases, and its density varies not only with its composition but also with its temperature and pressure. The water vapor content is an important consideration.

The formula for the density of air is given by the equation:

$$\varrho = \frac{P}{RT_V}$$

where P is the atmospheric pressure,
R is a constant (the gas constant),
T_V is the adjusted virtual temperature, a quantity which will now be defined.

4.4 The adjusted virtual temperature T_V. T_V is determined from the formula:

$$T_V = T_A(1 + 0.6q)$$

where T is the air temperature in absolute units (degrees Kelvin),
q is the specific humidity $\left(\frac{\varrho w}{\varrho d + \varrho w}\right)$,

ϱw is the water vapor density of the air,
ϱd is the density of dry air.

Thus, T_V is greater than the absolute temperature, T_A, of the air mass. In effect an increment is added to the actual air temperature to allow for water vapor content. Since water vapor is lighter than air, a parcel of air containing a high percentage of water vapor is lighter than the parcel of dry air by itself. Since density decreases with increase of temperature, the effect can be taken into consideration by assigning to the parcel a higher temperature than the one it actually possesses; the increment being added so that the two densities are equated. It is therefore a fictitious temperature defined as that equivalent temperature which a saturated air parcel would have if (when behaving perfectly as a gas) it possessed the same density as the dry air parcel.

Table 1 sets out the increments to be applied to T_A for cases of saturated air for eight different pressure values between 960 and 1030 millibars over a temperature range from −5 °C to +30 °C. Such ranges of temperature and pressure cover most synoptic situations encountered at sea level around the world.

Example I — If the air temperature of a saturated air mass is 15 °C and the pressure is 1020 millibars, we see from Table 1 that the adjusted virtual temperature is 16.8 °C. Thus, dry air at 16.8 °C has the same density as saturated air at 15 °C when the pressure is 1020 millibars. From Table 2 we see that the corresponding density to $T_V = 16.8$ °C is 1.2255 kg/cubic meter.

TABLE 1

INCREMENTS IN DEGREES CELSIUS TO APPLY TO T_A FOR SATURATED AIR TO OBTAIN THE ADJUSTED VIRTUAL TEMPERATURE

Air Temp. (°C)	Pressure (mb)							
	1030	1020	1010	1000	990	980	970	960
−5	0.42	0.42	0.43	0.43	0.43	0.44	0.44	0.45
−4	0.45	0.45	0.46	0.46	0.46	0.47	0.47	0.48
−3	0.48	0.49	0.49	0.50	0.51	0.51	0.52	0.53
−2	0.53	0.53	0.53	0.54	0.55	0.55	0.56	0.56
−1	0.57	0.57	0.58	0.59	0.60	0.60	0.61	0.61
0	0.61	0.62	0.63	0.64	0.65	0.65	0.66	0.66
1	0.66	0.67	0.68	0.68	0.69	0.70	0.71	0.71
2	0.71	0.72	0.73	0.74	0.75	0.76	0.77	0.77
3	0.76	0.77	0.78	0.79	0.80	0.81	0.82	0.83
4	0.82	0.83	0.84	0.85	0.86	0.87	0.89	0.90
5	0.89	0.90	0.91	0.92	0.93	0.94	0.96	0.97
6	0.96	0.97	0.98	0.99	1.00	1.01	1.03	1.04
7	1.04	1.05	1.06	1.07	1.08	1.09	1.10	1.11
8	1.11	1.13	1.14	1.15	1.16	1.17	1.19	1.20
9	1.19	1.20	1.22	1.23	1.24	1.26	1.28	1.30
10	1.28	1.30	1.31	1.32	1.34	1.36	1.38	1.40
11	1.37	1.39	1.40	1.42	1.44	1.46	1.48	1.50
12	1.47	1.49	1.51	1.52	1.54	1.56	1.58	1.60
13	1.57	1.59	1.61	1.63	1.65	1.67	1.69	1.70
14	1.68	1.70	1.73	1.75	1.77	1.79	1.81	1.82
15	1.81	1.83	1.85	1.87	1.89	1.91	1.94	1.95
16	1.94	1.96	1.98	2.00	2.02	2.05	2.08	2.10
17	2.07	2.10	2.13	2.15	2.17	2.20	2.22	2.24
18	2.23	2.26	2.28	2.30	2.32	2.35	2.38	2.41
19	2.38	2.41	2.43	2.46	2.49	2.52	2.55	2.58
20	2.55	2.58	2.60	2.62	2.65	2.68	2.71	2.74
21	2.72	2.75	2.78	2.80	2.83	2.86	2.90	2.93
22	2.90	2.93	2.96	2.99	3.03	3.06	3.10	3.13
23	3.09	3.13	3.16	3.19	3.23	3.26	3.30	3.34
24	3.29	3.33	3.37	3.40	3.44	3.48	3.52	3.55
25	3.52	3.56	3.59	3.62	3.66	3.71	3.76	3.79
26	3.74	3.78	3.82	3.86	3.90	3.95	4.00	4.04
27	4.00	4.04	4.08	4.11	4.16	4.21	4.26	4.30
28	4.25	4.30	4.34	4.38	4.43	4.48	4.53	4.57
29	4.52	4.57	4.62	4.67	4.72	4.77	4.83	4.88
30	4.82	4.87	4.92	4.97	5.02	5.07	5.12	5.18

TABLE 2

DENSITY OF AIR IN kg/m³

Adjusted Virtual Air Temperature T_V (°C)	Pressure (mb)							
	1035	1030	1025	1020	1015	1010	1005	1000
−4	1.3397	1.3332	1.3268	1.3203	1.3138	1.3073	1.3008	1.2943
−3	1.3347	1.3283	1.3219	1.3154	1.3090	1.3024	1.2955	1.2895
−2	1.3298	1.3234	1.3170	1.3105	1.3041	1.2976	1.2912	1.2848
−1	1.3249	1.3185	1.3121	1.3057	1.2993	1.2929	1.2865	1.2801
0	1.3200	1.3136	1.3073	1.3009	1.2945	1.2882	1.2818	1.2754
1	1.3151	1.3088	1.3024	1.2961	1.2898	1.2835	1.2770	1.2707
2	1.3103	1.3040	1.2977	1.2914	1.2851	1.2788	1.2724	1.2661
3	1.3056	1.2993	1.2930	1.2867	1.2804	1.2741	1.2678	1.2615
4	1.3009	1.2946	1.2984	1.2821	1.2758	1.2695	1.2632	1.2570
5	1.2962	1.2899	1.2837	1.2775	1.2713	1.2650	1.2587	1.2525
6	1.2915	1.2853	1.2791	1.2729	1.2667	1.2605	1.2642	1.2480
7	1.2869	1.2807	1.2745	1.2683	1.2621	1.2560	1.2497	1.2435
8	1.2824	1.2762	1.2700	1.2638	1.2576	1.2515	1.2453	1.2391
9	1.2779	1.2717	1.2655	1.2593	1.2531	1.2470	1.2408	1.2347
10	1.2734	1.2672	1.2610	1.2549	1.2487	1.2426	1.2364	1.2303
11	1.2690	1.2628	1.2566	1.2505	1.2443	1.2382	1.2321	1.2260
12	1.2646	1.2584	1.2522	1.2461	1.2400	1.2339	1.2278	1.2217
13	1.2602	1.2540	1.2478	1.2417	1.2536	1.2296	1.2235	1.2174
14	1.2557	1.2496	1.2435	1.2374	1.2313	1.2253	1.2192	1.2132
15	1.2514	1.2453	1.2392	1.2331	1.2271	1.2211	1.2150	1.2090
16	1.2471	1.2410	1.2349	1.2289	1.2229	1.2169	1.2108	1.2048
17	1.2427	1.2367	1.2307	1.2247	1.2187	1.2127	1.2066	1.2006
18	1.2384	1.2324	1.2264	1.2205	1.2145	1.2085	1.2025	1.1965
19	1.2342	1.2282	1.2222	1.2163	1.2103	1.2043	1.1983	1.1924
20	1.2300	1.2240	1.2180	1.2121	1.2061	1.2002	1.1942	1.1883
21	1.2257	1.2198	1.2139	1.2080	1.2020	1.1961	1.1902	1.1843
22	1.2216	1.2157	1.2098	1.2039	1.1980	1.1921	1.1862	1.1803
23	1.2175	1.2116	1.2057	1.1998	1.1939	1.1881	1.1822	1.1763
24	1.2134	1.2075	1.2016	1.1958	1.1899	1.1841	1.1782	1.1724
25	1.2094	1.2035	1.1977	1.1918	1.1859	1.1801	1.1743	1.1685
26	1.2053	1.1995	1.1936	1.1878	1.1819	1.1761	1.1703	1.1646
27	1.2013	1.1955	1.1897	1.1839	1.1780	1.1722	1.1665	1.1607
28	1.1973	1.1915	1.1858	1.1800	1.1741	1.1683	1.1625	1.1568
29	1.1933	1.1876	1.1818	1.1761	1.1703	1.1645	1.1587	1.1530
30	1.1895	1.1837	1.1780	1.1723	1.1665	1.1607	1.1550	1.1492
31	1.1856	1.1799	1.1742	1.1685	1.1628	1.1569	1.1512	1.1454
32	1.1818	1.1761	1.1704	1.1647	1.1589	1.1531	1.1474	1.1417

TABLE 2

DENSITY OF AIR IN kg/m^3

Adjusted Virtual Air Temperature T_v (°C)	Pressure (mb)							
	995	990	985	980	975	970	965	960
−4	1.2878	1.2813	1.2749	1.2685	1.2620	1.2555	1.2490	1.2425
−3	1.2831	1.2767	1.2703	1.2638	1.2574	1.2509	1.2444	1.2380
−2	1.2784	1.2720	1.2653	1.2591	1.2527	1.2463	1.2400	1.2336
−1	1.2737	1.2673	1.2609	1.2544	1.2480	1.2417	1.2354	1.2291
0	1.2690	1.2626	1.2562	1.2498	1.2434	1.2371	1.2308	1.2245
1	1.2643	1.2580	1.2516	1.2452	1.2389	1.2325	1.2262	1.2200
2	1.2597	1.2534	1.2470	1.2407	1.2343	1.2280	1.2217	1.2154
3	1.2552	1.2489	1.2426	1.2362	1.2299	1.2236	1.2173	1.2110
4	1.2507	1.2444	1.2381	1.2318	1.2255	1.2192	1.2129	1.2066
5	1.2462	1.2399	1.2337	1.2274	1.2212	1.2148	1.2085	1.2022
6	1.2418	1.2355	1.2292	1.2230	1.2267	1.2105	1.2042	1.1980
7	1.2373	1.2311	1.2248	1.2186	1.2124	1.2062	1.2000	1.1938
8	1.2329	1.2267	1.2205	1.2143	1.2081	1.2019	1.1957	1.1895
9	1.2285	1.2223	1.2161	1.2100	1.2038	1.1976	1.1914	1.1852
10	1.2241	1.2180	1.2118	1.2057	1.1995	1.1934	1.1872	1.1810
11	1.2198	1.2137	1.2075	1.2014	1.1853	1.1892	1.1831	1.1770
12	1.2155	1.2094	1.2033	1.1972	1.1911	1.1850	1.1789	1.1728
13	1.2113	1.2052	1.1991	1.1930	1.1870	1.1809	1.1748	1.1687
14	1.2071	1.2010	1.1950	1.1889	1.1828	1.1768	1.1708	1.1647
15	1.2029	1.1969	1.1908	1.1848	1.1787	1.1727	1.1667	1.1606
16	1.1988	1.1928	1.1867	1.1807	1.1746	1.1686	1.1626	1.1566
17	1.1946	1.1886	1.1826	1.1766	1.1705	1.1645	1.1585	1.1525
18	1.1905	1.1846	1.1786	1.1726	1.1665	1.1605	1.1545	1.1485
19	1.1864	1.1805	1.1745	1.1685	1.1625	1.1565	1.1505	1.1445
20	1.1824	1.1765	1.1705	1.1646	1.1586	1.1526	1.1466	1.1406
21	1.1784	1.1725	1.1665	1.1606	1.1547	1.1487	1.1427	1.1368
22	1.1744	1.1685	1.1626	1.1567	1.1508	1.1449	1.1390	1.1331
23	1.1704	1.1646	1.1587	1.1528	1.1470	1.1411	1.1352	1.1293
24	1.1666	1.1607	1.1548	1.1489	1.1431	1.1373	1.1315	1.1257
25	1.1626	1.1568	1.1509	1.1441	1.1393	1.1335	1.1277	1.1219
26	1.1588	1.1529	1.1472	1.1413	1.1355	1.1297	1.1240	1.1183
27	1.1549	1.1491	1.1433	1.1375	1.1317	1.1259	1.1201	1.1143
28	1.1510	1.1453	1.1395	1.1337	1.1280	1.1222	1.1164	1.1106
29	1.1472	1.1415	1.1357	1.1300	1.1242	1.1185	1.1128	1.1071
30	1.1435	1.1377	1.1320	1.1263	1.1205	1.1148	1.1091	1.1034
31	1.1397	1.1340	1.1283	1.1226	1.1168	1.1111	1.1054	1.0997
32	1.1360	1.1303	1.1246	1.1189	1.1132	1.1075	1.1018	1.0960

4. 5 The density of partially saturated air. To obtain the density of an air mass it is first necessary to adjust its temperature to allow for the water vapor content. In practice most air masses are only partially saturated. Table 1 sets out the increments to be applied to T for the case of saturated air. But only a proportion of the increment will be necessary if the air is partially saturated. The equations which govern this portion contain a number of parameters and will not be quoted in detail. It will be sufficient for most practical applications to use the approximation:

$$i = \frac{(RH)}{100} \times I$$

where i is the increment to be applied for the partially saturated air,
I is the increment for saturated air (obtained from Table 1),
RH is the relative humidity.

The relative humidity is expressed as a percentage and can be determined from psychrometric tables using the dry and wet bulb temperatures.

To obtain the density of any air mass:

(1) Obtain the relative humidity (RH) from the wet and dry bulb readings.
(2) Find the increment I from Table 1 corresponding to the temperature T and pressure value P for saturated air.
(3) Calculate $\frac{(RH)}{100} \times I$ and add the value to T.
(4) Use Table 2 to determine ρa.

Example II — Suppose the air temperature is 15 °C and the relative humidity is 60% and the surface pressure 1020 mb. From Table 1, I = 1.8 °C. The increment to be applied is 60% of 1.8 °C or 1.1 °C; hence, the adjusted virtual temperature is 16.1 °C. The density is 1.2285 kg/cubic meter (see Table 2).

4.6 Approximation for density difference ($\rho a - \rho s$) using temperatures and ignoring pressure changes. At any given pressure, ρs is proportional to $\frac{1}{T_{SV}}$ where T_{SV} is the virtual temperature corresponding to the sea surface temperature T_S. Let $T_{SV} = T_S + t_S$, where t_S is the increment determined from Table 1.

The assumption is made that the air in immediate contact with the sea surface is saturated. In Table 1, values of increments vary from 0.6 °C to 5.2 °C in the range of temperatures between −1 °C and 30 °C, which covers the sea surface temperatures generally observed.

Similarly, ρa is proportional to $\frac{1}{T_{AV}}$ where T_{AV} is the virtual temperature corresponding to the air temperature T_A.

Let $T_{AV} = T_A + t_X$, where t_X is the increment from Table 1 that has been adjusted for the relative humidity of the partially saturated air.

The air mass will not necessarily be saturated in every case, and the values of the increments derived from Table 1 will have to be adjusted according to the humidity.

$$\rho a - \rho s \propto \frac{1}{T_{AV}} - \frac{1}{T_{SV}} = \frac{1}{(T_A + t_X)} - \frac{1}{(T_S + t_S)}$$

$$= \frac{(T_S - T_A) + (t_S - t_X)}{(T_A + t_X)\,(T_S + t_S)}$$

Let us examine this relationship to determine how far it is justified to assume that ($\rho a - \rho s$) is proportional to ($T_S - T_A$), the difference in sea and air temperatures.

Only if ($T_S - T_A$) is small and if the air mass has a high relative humidity can we neglect ($t_S - t_X$) and make the direct assumption that ($\varrho a - \varrho s$) is proportional to ($T_S - T_A$). To make the assumption that $t_S = t_X$, ($T_S - T_A$) should be no greater than one or two degrees centigrade. In the case where T_A is several degrees lower than T_S and the air mass is relatively dry, for example, in the wake of a cold or arctic front, the value of ($t_S - t_X$) is not negligible.

Let us consider a practical example where T_S is 12 °C, T_A is 8 °C, and the relative humidity is 50%. Assume a constant pressure of 1000 millibars. Round off values from Table 1 to nearest 0.1 °C.

$T_{AV} = 273 + 8 + (1/2)(1.2) = 281.6\,°K$
$T_{SV} = 273 + 12 + (1)(1.5) = 286.5\,°K$
$T_S - T_A = 4°$, whereas $T_{SV} - T_{AV} = 4.9°$

In this simple case, the effect of density difference is underestimated about 18% by using the factor ($T_S - T_A$) as the indicator.

4.7 Relative importance of pressure, temperature, and humidity changes. An examination of a few specific examples using Tables 1 and 2 is instructive and will enable you to understand the relative impact of variations of pressure, temperature, and humidity on the density of air at sea level.

An examination of Table 2 shows that for any specified temperature, the density of air is about 6% less at an atmospheric pressure of 970 millibars than it is at 1035 millibars. Again, for any specific pressure (*e.g.*, 1000 millibars), the density is about 10% less at 30 °C than it is at 0 °C. Thus, temperature changes are relatively more important than pressure changes, but when the effects are cumulative, the difference may exceed 15%. This explains why cold dry air masses are more effective in raising steep seas quickly than warm humid ones.

Ignoring the humidity of the atmosphere does not generally affect the density by more than 1%, but the significant point to appreciate is that sea and swell generation depends on the degree of contact that occurs between air and sea; this is proportional to the density difference $\varrho a - \varrho s$. Although changes in actual density may be almost negligible, they can result in comparatively large proportional increases in $\varrho a - \varrho s$. This is best illustrated by considering an example.

Example III — Let us suppose that an air mass of temperature 17 °C and relative humidity 50% is flowing over a sea surface of temperature 18 °C; the pressure being constant at 1000 millibars. From Table 1, we see that the virtual temperature to determine ϱa is $17 + 0.5 \times 2.15 = 18.1$ °C and to determine ϱs is $18 + 2.30 = 20.3$ °C.

Using these values in Table 2, $\varrho a - \varrho s = 1.1961 - 1.1871 = 0.0090$. If we had ignored humidity and used the corresponding values for $T_A = 17$ °C ($\varrho a = 1.2006$) and $T_S = 18$ °C ($\varrho s = 1.1965$) in Table 1, a density difference of 0.0041 would have resulted. This is only about 45% of the actual difference.

Example IV — Let us consider the practical case of a deep depression with a central pressure of 980 millibars passing over a water surface followed by an anticyclone with a very rapid rise in pressure to 1010 millibars. Let us further assume that the air mass in advance of the depression was relatively warm and humid, the temperature being 12 °C, the relative humidity 90%, and that subsequently, the temperature fell to 1 °C with relative humidity 40%. This is approximately the sequence of events recorded during the passage of the storm across Lake Superior on 10-11 November 1975 (see Chapter 3). Let us consider the density changes in the atmosphere for the period.

From Table 1 the following adjusted virtual temperatures are obtained:

Prior to the wind shift: (P = 980 mbs.) and $T_{AV} = 12 + 90\%$ of $1.56 = 13.4$ °C.

After the wind shift: (P = 1010 mbs.) and $T_{AV} = 1 + 40\%$ of $0.68 = 1.3$ °C.

From Table 2 we obtain the following corresponding densities of air masses:

Before: $\varrho a_1 = 1.1914$ kg/m^3

After: $\varrho_{a1} = 1.2821\ \mathrm{kg/m^3}$

We can see that there was about a 7% increase in the density of the air mass blowing over the water.

Let us now compute the density of the air directly in contact with the water and compare this with the density of the air blowing over the water. Assume a water temperature of 8 °C and the same atmospheric pressures as above. From Table 1, the adjusted virtual temperatures are:

Before the wind shift: $T_{SV1} = 8 + 100\%$ of $1.17 \cong 9.2\ ^\circ\mathrm{C}$

After the wind shift $T_{SV2} = 8 + 100\%$ of $1.14 \cong 9.1\ ^\circ\mathrm{C}$

From Table 2, the corresponding densities are:

Before: $\varrho_{S1} = 1.2091\ \mathrm{kg/m^3}$

After: $\varrho_{S2} = 1.2466\ \mathrm{kg/m^3}$

Comparing the density differences, we get the following results:

Before the wind shift: $(\varrho_{a1} - \varrho_{S1}) = -0.0177\ \mathrm{kg/m^3}$

After the wind shift: $(\varrho_{a2} - \varrho_{S2}) = +0.0355\ \mathrm{kg/m^3}$

As we can see, the density difference between the air immediately in contact with the water and the air blowing over the water is much greater after the wind shift when the colder air arrived.

4.8 The effect of air density differences in cases of limited fetch or duration. Various diagrams exist that show the limitations imposed by either fetch or duration on significant wave heights (*e.g.*, the graphs given in Chapter 7 prepared by Mollie Darbyshire and L. Draper).

Other diagrams, more appropriate to areas of open ocean, are to be found in Chapter 11 giving the co-cumulative spectra corresponding to various wind speeds. Curves are drawn on these diagrams from which it is possible to assess the amount of energy contained in a partially arisen sea. All such diagrams give values comparable to one another for any given wind speed, but you should be aware that they are average circumstances prepared from a limited series of measurements. They do not take into account air density changes, and particular the density difference $(\varrho a - \varrho s)$. It is often this latter factor which will determine how quickly the sea gets up with a weather change and how steep the waves will become in the initial stages. This is usually the most important information required by the seaman.

Lumb's diagrams (see Chapter 7) and the modifications to his diagrams proposed by Britton make some allowance for air mass characteristics, but there are no precise rules or laws for indicating which lines or curves to employ. Other diagrams due to Verploegh use the difference between sea and air temperature as the basis for calculations, but as we have seen, these differences provide only a rough approximation to the effects resulting from density variations. The limitations of most of these diagrams are illustrated by the following example.

Example V — Let us compare and contrast two realistic synoptic situations for a fixed station situated equidistantly 100 miles from coastlines as in Figure 7. The example could be considered to apply to an oil rig in the North Sea half way between Norway and the United Kingdom.

The wind speed in both cases is 36 knots with a limited fetch of 100 miles. From the usual diagrams available to forecasters, equal significant wave heights of approximately 13 feet might be deduced after an interval of nine hours for both situations. The maximum significant wave height created by a 36 knot wind with an unlimited duration and fetch would be about 21 feet and would require a minimum fetch of about 500 miles and a minimum duration of 34 hours.

Situation (1): a typical winter anticyclonic situation in which the following circumstances prevailed at point X:

Pressure: 1030 millibars, associated with an anticyclone over Norway
Wind: east-northeast 36 knots
Air temperature: +3 °C
Dew point: −2 °C
Relative humidity: 69%
Sea surface temperature: + 8 °C

Situation (2): a summer cyclonic situation with a low center crossing the area. Data at point X:

Pressure: 980 millibars
Wind: blowing from the reverse direction to that of situation (1), west-southwest at 36 knots
Air temperature: +15 °C
Dew point: +14 °C
Relative humidity: 94%
Sea surface temperature: +17 °C

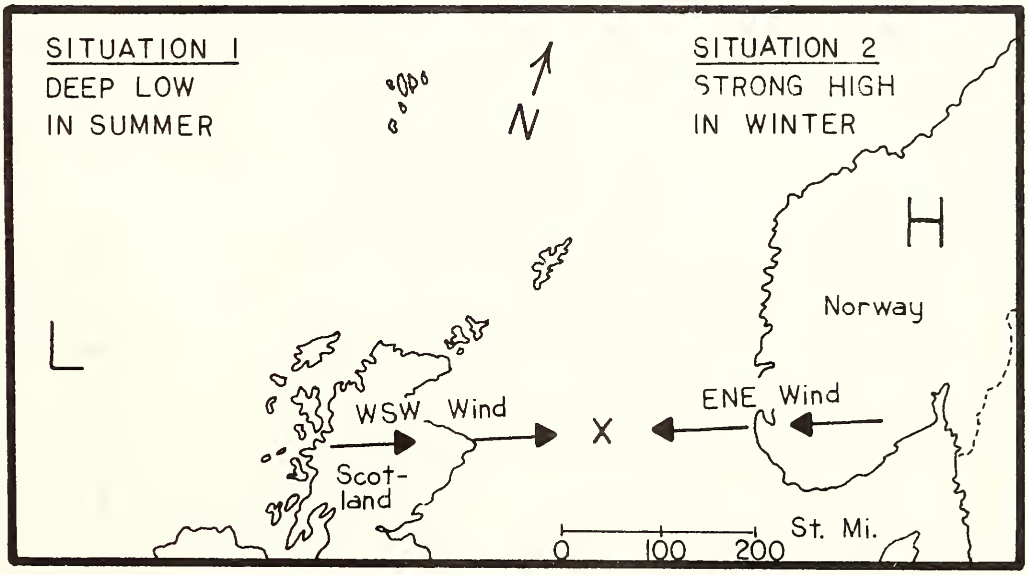

Figure 7—Two hypothetical contrasting situations in the North Sea.

Situation 1 (Winter)

ϱ_{a1} = 1.2969 kg/m^3
ϱ_{s1} = 1.2712 kg/m^3

Situation 2 (Summer)

ϱ_{a2} = 1.1774 kg/m^3
ϱ_{s2} = 1.1677 kg/m^3

It is seen that in situation (1) not only is the air mass 10% heavier than it is in situation (2), but the difference,

$\varrho_{a1} - \varrho_{s1} = .0257$, is over 2.5 times greater than $\varrho_{a2} - \varrho_{s2} = .0097$ in situation (2). Thus, not only is the driving force heavier, but there is a considerably larger impact force. It is not to be expected that the rate of generating sea and swell would be the same in both cases. It is suggested that situation (1) could well result in significant wave heights in excess of 18 feet at point X within six hours, whereas there would be little more than 10 feet after 10 hours in situation (2). The steepness of the waves after two or three hours would be much greater in sutuation (1) than in situation (2). At present no guidance exists to help the forecaster to quantify the amounts obtained from the standard diagrams and procedures. More research is necessary and long series of recorded data are required to improve the empirical formulas in the formative stages of sea and swell development. In the meantime, forecasters should make some allowances based on common sense considerations of density values.

CHAPTER

5

THE DYNAMICS OF THE BOUNDARY LAYER IN THE ATMOSPHERE

5.1 Surface wind. The behavior of the smoke in rocket trails described in Chapter 3 indicates the effect of stability on wind speed and direction variations with height in the lower atmosphere. It follows that there is a requirement for a definition of surface wind speed and direction. Wind reports from ships are preferably measured or estimated at a height of 10 meters, and the wind vector at this height is usually referred to as the surface wind velocity. But this is not the wind which is generating sea and swell at surface level. There is obviously a need for another definition of a wind value closer to the sea surface for determining the sea and swell generated.

Most wind observations reported and recorded by ships are estimations based upon the visual effects which the wind has on the sea surface, and there is little to improve upon the scale formulated by Beaufort more than 100 years ago to estimate wind force from the sea appearance. The Beaufort wind scale (Table 3) is widely used by mariners and is capable of fairly precise conversions into knots or meters per second. Where wind observations are made by skilled observers this provides the best guide for a sea and swell forecaster to calculate wave heights and periods. It follows that a wind estimation made by this means is not the surface wind as defined by the World Meteorological Organization.

The Beaufort wind force may be considered to be the wind very close to the actual surface and will be defined as the "effective wind" since it is about the closest approximation possible to the wind which sets the sea in motion.

Few ships are equipped with anemometers to measure wind speed, but these instruments do not necessarily provide better results since the values depend much on quality of exposure which changes with every course change of the ship. Also they can seldom be sited at the exact height of 10 meters above sea surface. Aircraft carriers are highly dependent on obtaining a "true" wind speed and direction for safety of flight, and they carry three or more anemometers, which is considered sufficient for at least one of them to have a good exposure.

It is not uncommon for the anemometers to indicate sensibly different values at the different levels at which they are placed, and it is a matter of experience to know which relative reading to use. At best these winds are only relative winds for they need to be corrected with the ship's course and speed to deduce the true wind at or near 10 meters. Another correction is then necessary to derive the effective wind at sea level. It is often assumed that the wind change with height follows a logarithmic law, but as we have seen from the smoke profiles it is only justified to make this assumption when the atmosphere is unstable, and humidity ducts are largely absent or weak.

The following empirical formula is quoted for reducing wind speed observations made at a height Z to a height of one meter above sea surface and is based on observations made in the Caspian, Baltic, and Bering Seas:

$$U_1 = U_Z - \log (U_Z + 1.0)\,[a\,(t_Z - t_W) + b]$$

where $a = 0.19 \log Z + 0.37$,
$b = 0.80 \log Z + 0.24$,
U_1 = wind speed at one meter in meters/sec,
U_Z = wind speed measured at height Z in meters/ sec,
t_Z = Air temperature at height Z,
t_W = sea surface temperature.

This is a typical logarithmic type formula suitable for unstable conditions. It is less accurate when the air mass is much warmer than the sea surface.

TABLE 3

BEAUFORT WIND SCALE

Beaufort number	Wind speed				Seaman's term		Estimating wind speed	
	knots	mph	meters per second	km per hour			Effects observed at sea	Effects observed on land
0	under 1	under 1	0.0-0.2	under 1	Calm	Light	Sea like mirror.	Calm; smoke rises vertically.
1	1-3	1-3	0.3-1.5	1-5	Light air		Ripples with appearance of scales; no foam crests.	Smoke drift indicates wind direction; vanes do not move.
2	4-6	4-7	1.6-3.3	6-11	Light breeze		Small wavelets; crests of glassy appearance, not breaking.	Wind felt on face; leaves rustle; vanes begin to move.
3	7-10	8-12	3.4-5.4	12-19	Gentle breeze	Gentle	Large wavelets; crests begin to break; scattered whitecaps.	Leaves, small twigs in constant motion; light flags extended.
4	11-16	13-18	5.5-7.9	20-28	Moderate breeze	Moderate	Small waves, becoming longer; numerous whitecaps.	Dust, leaves, and loose paper raised up; small branches move.
5	17-21	19-24	8.0-10.7	29-38	Fresh breeze	Fresh	Moderate waves, taking longer form; Many whitecaps; some spray.	Small trees in leaf begin to sway.
6	22-27	25-31	10.8-13.8	39-49	Strong breeze	Strong	Larger waves forming; whitecaps everywhere; more spray.	Larger branches of trees in motion; whistling heard in wires.
7	28-33	32-38	13.9-17.1	50-61	Moderate gale		Sea heaps up; white foam from breaking waves begins to be blown in streaks.	Whole trees in motion; resistance felt in walking against wind.
8	34-40	39-46	17.2-20.7	62-74	Fresh gale	Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks.	Twigs and small branches broken off trees; progress generally impeded.
9	41-47	47-54	20.8-24.4	75-88	Strong gale		High waves; sea begins to roll; dense streaks of foam; spray may reduce visibility.	Slight structural damage occurs; slate blown from roofs.
10	48-55	55-63	24.5-28.4	89-102	Whole gale	Whole Gale	Very high waves with overhanging crests; sea takes white appearance as foam is blown in very dense streaks; rolling is heavy and visibility reduced.	Seldom experienced on land; trees broken or uprooted; considerable structural damage occurs.
11	56-63	64-72	28.5-32.6	103-117	Storm		Exceptionally high waves; sea covered with white foam patches; visibility still more reduces.	Very rarely experienced on land; usually accompanied by widespread damage.
12	63-71	73-82	32.7-36.9	118-133	Hurricane	Hurricane	Air filled with foam; sea completely white with driving spray; visibility greatly reduced.	
13	72-80	83-92	37.0-41.4	134-149				
14	81-89	93-103	41.5-46.1	150-166				
15	90-99	104-114	46.2-50.9	167-183				
16	100-108	115-125	51.0-56.0	184-201				
17	109-118	126-136	56.1-61.2	202-220				

5.2 The geostrophic wind. Meteorologists commonly use a term, the geostrophic wind, which is the wind readily derived from a weather chart. Basically, air tends to flow from one point A on the earth's surface towards another point B because of a pressure difference or pressure gradient existing between A and B. The flow is not direct because the motion takes place over the curved surface of the earth, but it is possible to relate the wind speed to the pressure difference.

On weather maps, isobars are drawn joining places having equal surface pressure values, and the speed of the air stream may be estimated from the degree of separation of the isobars. But the relationship is not direct because of the Coriolis effect that is proportional to the sine of the latitude. In addition, near the ground or sea surface the air is subject to a frictional effect at all times. Hence, the wind speed deduced from the measurement of separation of isobars -the geostrophic wind- may be considered as the wind at a height where the frictional effect is nearly negligible, and this is usually some 300 or 400 meters above sea level.

A mathematical formula for a geostrophic wind is

$$U_{gs} = -\frac{1}{f\varrho}\,\frac{dp}{dn}$$

where U_{gs} is the geostrophic wind speed,

$\frac{dp}{dn}$ is the pressure gradient normal to the isobars.

f is the Coriolis coefficient which is proportional to the sine of the latitude. $f = 2\Omega \sin\phi$ where Ω is the angular velocity of the earth and ϕ = latitude,

ϱ is the density of the air.

The formula only applies to the flow of a steady air stream (*i.e.,* one which is constant in direction and is not accelerating). A simple consideration of the terms shows that the relationship tends to be meaningless at low latitudes.

5.3 The relationship between the geostrophic wind and the effective wind at sea level. In order to provide useful and accurate environmental services to the shipping and fishing industries, effective forecast winds at surface level are required from which sea and swell heights can be deduced. The basic tool for this task is the most recent surface synoptic weather chart on which all the ship reports available are plotted. From the pressure analysis, geostrophic winds can be deduced and standard techniques applied to derive the effective winds at surface level. In the temperate latitudes these would be used in combination with all wind data from ships, to draw isopleths of wind velocity. Over areas from which no shipping reports are available a forecaster must use geostrophic winds as the basis for deriving the effective winds. Also he must use prognostic pressure charts for forecasting sea and swell heights at future times, and he has no alternative but to derive effective winds from geostrophic values. Since modern policies are to avoid manual plotting as far as possible and derive all products by computer techniques, the tendency increases to derive all effective winds from pressure analysis. This procedure often discounts the wind data reported by ships, which is perhaps even more reliable than the pressure data reported. It leads to unsatisfactory sea and swell computer outputs.

The relationship between the geostrophic wind and the effective surface wind is not simple, for several corrections should be taken in the following order:

(a) It is first necessary to apply a correction for the curvature of the isobars. In a very intense cyclonic situation, the gradient wind, which takes account of a curved flow path of the wind, may be less than half the geostrophic wind. Forecasters do not always appreciate that high seas and swells do not result only from intense storms with closely packed isobars near a deep center. Worse conditions may result from an anticyclone which has closely packed straight isobars extending over a considerable distance. This is particularly true when an outbreak of cold air from arctic regions follows an intense storm. The seas and swells will often increase in height after the depression moves away or has started to fill.

(b) After a correction has been applied for the curvature of the isobars, consideration must be given to the stability of the atmosphere (see paragraph 5.6).

5.4 The gradient wind. Assuming that the geostrophic wind speed can be measured at any point on a surface synoptic chart, a rough approximation to the surface wind can be made by taking 70% of the geostrophic wind speed and applying a rotation of about 15° – 30° to the direction of the isobars to get the wind direction. This rough approximation is insufficient to give a good sea and swell forecast. A more accurate correction must be applied for the curvature of the isobars to obtain the gradient wind. (In actuality, the curvature of the streamlines, not the isobars, should be used. This is usually not practical for an operational forecaster because a streamline chart has to be prepared. A textbook on meteorological analysis will explain the techniques involved and the types of errors that occur when isobars are used.) In cyclonic situations the gradient wind is less than the geostrophic wind by an amount equal to:

$$\frac{U_{gr}^2}{rf}$$

where U_{gr} = gradient wind speed,
r = radius of curvature of the isobars,
f = Coriolis coefficient $(2\Omega \sin\phi)$.

This correction can have considerable value when r is small and wind speeds are great as they are in an intense storm. In practice, the aim is to obtain the effective wind field quickly from the isobaric chart; hence, too much weight need not be attached to a correction unless the geostrophic wind is in excess of 25 knots and the radius of curvature of the isobars is less than 10° latitude (600 nm or 1110 km).

The following approximate method of estimating the gradient wind may be used in the belt of latitude from 40° – 65° where most extra-tropical depressions are encountered. Measure the geostrophic wind speed *in knots* and the radius of curvature in *degrees of latitude* and determine U^2/r.

If U^2/r is less than 25 the cyclostrophic correction can be neglected.
If U^2/r lies between 25 and 50, reduce U by 5%.
If U^2/r lies between 50 and 100, reduce U by 10%.
If U^2/r lies between 100 and 200, reduce U by 15%.
If U^2/r lies between 200 and 300, reduce U by 20%.
If U^2/r lies between 300 and 400, reduce U by 25%.
If U^2/r lies between 400 and 600, reduce U by 30%.
If U^2/r lies between 600 and 1000, reduce U by 40%.
If U^2/r lies between 1000 and 15000, reduce U by 50%.
If U^2/r is greater than 1500, reduce U by 60%.

In areas of high pressure of anticyclones, the gradient wind is greater than the geostrophic wind, but the radius of curvature is normally so large that a correction is unnecessary. The same rule applies except that the geostrophic wind must be *increased* and not *decreased* by the percentages given above. The consideration also applies when using Tables 4, 5, and 6.

Another method is to use nomographs (notably Rudloffs) to facilitate accurate computations, but their use is time consuming. The following tables to derive gradient winds from geostrophic winds are given for three belts of latitude, 30° – 37°, 38° – 47°, and 48° – 60°, may be preferred and will give sufficient accuracy quickly.

TABLE 4

GRADIENT WINDS (latitudes 30° – 37°)

	Radius of curvature of isobars in degrees of latitude										
U_{gs}(kn)	1°	1.5°	2°	2.5°	3°	4°	5°	6°	8°	10°	12.5°
20	12	13	14	15	15	16	17	17	18	18	19
25	14	16	17	18	18	20	20	21	22	22	23
30	16	18	19	20	21	23	24	24	26	26	27
35	18	20	22	23	24	26	27	28	29	30	31
40	19	22	24	26	27	28	30	31	33	34	35
45	21	24	26	28	29	31	33	34	36	37	39
50	22	25	28	30	32	34	36	37	39	41	42
60	25	29	32	34	26	39	41	43	46	47	49
70	28	32	35	38	40	43	46	48	52	54	56
80	30	35	38	41	44	48	51	53	57	60	63

TABLE 5

GRADIENT WINDS (Latitudes 38° – 47°)

	Radius of curvature of isobars in degrees of latitude									
U_{gs}(kn)	1°	1.5°	2°	2.5°	3°	4°	5°	6°	8°	10°
20	12	14	15	16	16	17	17	17	18	18
25	14	16	18	19	19	20	21	21	22	23
30	17	19	20	21	22	24	25	25	26	27
35	19	21	23	24	25	27	28	29	30	31
40	20	23	25	27	28	30	31	32	34	35
45	22	25	27	30	32	33	34	36	37	38
50	24	27	29	31	33	35	37	39	40	42
60	26	30	33	36	38	41	43	45	46	49
70	30	34	37	40	42	44	49	52	54	56
80	32	36	40	43	46	49	53	56	59	62

TABLE 6

GRADIENT WINDS (Latitudes 48° – 60°)

	Radius of curvature of isobars in degrees of latitude									
U_{gs}(kn)	1°	1.5°	2°	2.5°	3°	4°	5°	6°	8°	10°
20	13	14	15	16	16	17	17	18	18	19
25	16	17	18	19	20	21	22	22	22	23
30	18	20	21	22	23	24	25	26	26	27
35	20	22	24	25	26	28	29	30	31	32
40	22	24	26	28	29	30	32	33	34	35
45	24	27	29	31	32	34	35	37	38	39
50	25	28	31	33	35	37	38	40	42	43
60	28	32	36	39	42	42	44	46	49	50
70	32	36	40	42	44	48	50	52	55	57
80	34	37	43	36	49	53	56	58	62	64

5.5 Corrections according to the atmospheric stability. It has long been recognized that the relationship between the surface wind and the geostrophic wind depends on the air temperature and the sea surface temperature. The work of Verploegh (and others) demonstrates the use of various nomographs and graphical techniques based upon an approximate linear relationship between the air and sea surface temperature (SST) difference and the ratio of the surface to the gradient wind. This ratio varies from a value of 0.60 when the air temperature is markedly higher than the sea surface temperature to 0.95 when the reverse is the case, and the overlying atmosphere is very unstable. In effect it assumes that the difference in the two temperature parameters reflects the degree of stability of the lower atmosphere.

But as was demonstrated by the smoke traces discussed in Chapter 3, the degree of contact exercised between an air mass and the sea surface is partially dependent on the relative humidity of the air stream. This suggests that the humidity factor ought to be included in all formulas and procedures used in computer models to obtain the surface wind from the geostrophic wind. Accepted formulas for evaporation from the sea surface, such as the Dalton type formula, (see equation 9.1), all include the term $(e_w - e_a)$, where e_w is the saturated water vapor pressure at the surface (directly proportional to the sea surface temperature), and e_a is the actual water vapor pressure of the air mass (determined from dry and wet bulb readings at deck level). This is a better factor to employ for determining the stability than $T_{sea} - T_{air}$ although there is the disadvantage that tables of water vapor pressure are not generally carried aboard ships. However, there is no reason why this factor should not be incorporated in numerical models and particularly so for deriving effective wind fields from prognostic surface pressure charts.

The graph of water vapor pressure is shown plotted in Figure 8 for the range of temperature from −5° to +20 °C. It is a simple matter to determine $e_w - e_a$ using dry and wet bulb temperatures and the sea surface temperature.

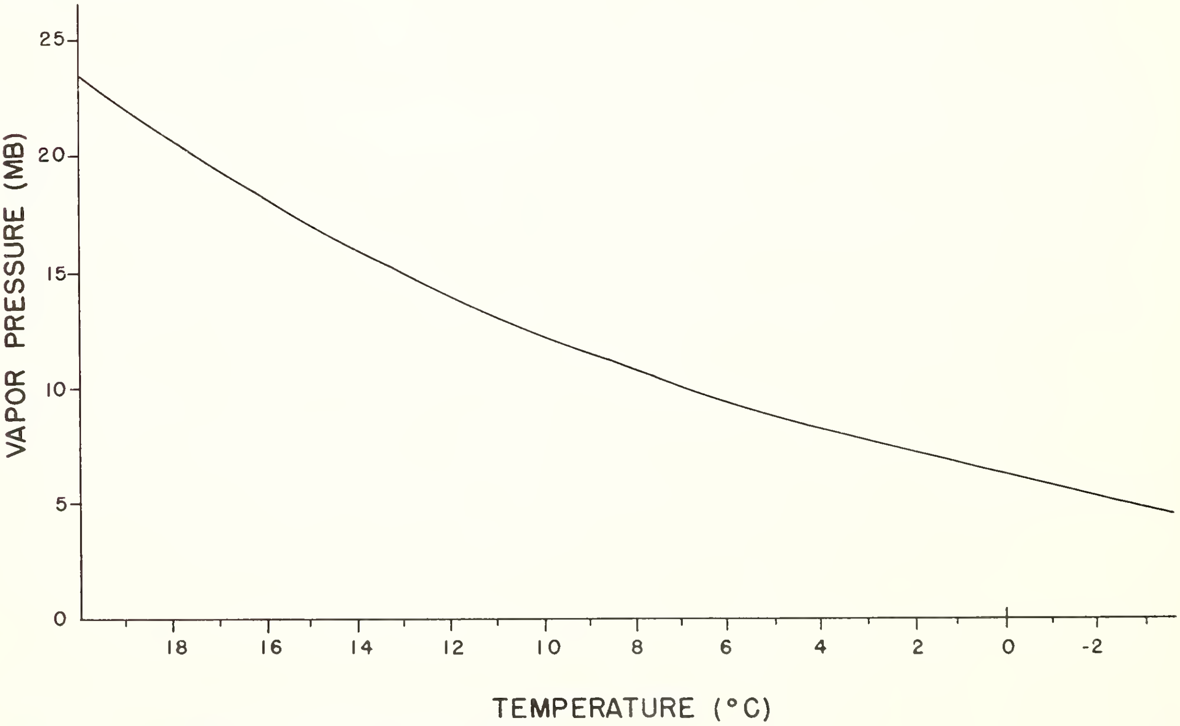

Figure 8 - Graph of water vapor pressure versus temperature.

5.6 Ratios of effective wind to the gradient wind. To determine the ratio applied to a gradient wind or measured wind to obtain the effective surface wind, it is first necessary to categorize the air mass relative to the sea surface temperature. (No correction needs to be applied to wind speed based on the Beaufort wind force since the estimated wind is the effective wind.) Five air mass/sea surface temperature categories are defined for this purpose, which are considered in greater detail in Chapter 7. Roughly, they are given as (1) very unstable, (2) unstable, (3) average, (4) stable, and (5) very stable. In making the classification, it is desirable to consider several parameters, including the satellite cloud pictures. The ratios to apply to a gradient wind to obtain the effective wind will be stated as follows:

(1) Very unstable: Multiply the gradient wind by 0.95.

(2) Unstable: multiply the gradient wind by 0.90.

(3) Average: multiply the gradient wind by 0.80.

(4) Stable: multiply the gradient wind by .070 for winds over 12 knots and 0.60 for winds less than 12 knots.

(5) Very stable: multiply the gradient wind by 0.60 for winds over 12 knots and 0.50 for winds less than 12 knots.

5.7 Plotting and analyzing an effective wind field chart. In a marine analysis center, at least one sea surface synoptic chart should be analyzed daily by manual means using all available shipping observations. Some modifications are suggested to the usual standard plotting procedures to facilitate the subsequent drawing of isopleths of effective wind velocity. Details of the proposed modifications to the standard plotting model are:

(1) The station circle indicating the total cloud cover can be left empty initially, but is filled in later with the deduced effective wind speed after considerations of the atmospheric stability. (The two examples below show the effective wind speeds inside the circle.)

(2) A forked tail is put on the wind direction, and the wind speed is put in the tail of the arrow. (An alternate method with more visual impact is shown in Figure 9.)

(3) An arrow indicates the swell with the reported swell height in the tail of the arrow. The period of the swell is noted alongside.

(4) The pressure and barometric tendency are plotted as normally.

(5) The air temperature, dew point temperature, and sea surface temperature and low cloud type are also plotted as normally, and from these the air mass/sea surface temperature classification is deduced.

(6) The present weather is plotted if it indicates fog or precipitation. Visibility figures (in code) are also plotted for low visibility.

(7) The period (in seconds) and height (in feet) of the sea are plotted in the position normally occupied by the medium and high cloud.

(8) The ship's heading and speed (in code) are denoted above the model. Thus, a plot takes the form shown in Figure 9.

Plot I indicates:
a. Surface wind of 25 kn from 250° true.

b. The wind waves (sea) have a period of 6 seconds and significant height of 8 feet.
c. The swell is of height 10 feet, from 290° true, and has a period of 9 seconds.
d. Barometer: 1003.2 mb. Tendency: 0.5 mb, rising.
e. Air temperature: 8 °C. Dew point temperature: 8 °C. Sea surface temperatures: 7.2 °C.
f. Present weather: moderate continuous rain.
g. Low cloud type: fractostratus and/or fractocumulus of bad weather. Past weather; none plotted as it was not significant.
h. The heading of the ship is NW at 6-10 kn (code figure 2).

It can be inferred that the atmosphere is stable. From the data shown , the air mass/sea surface temperature classification is 4, and the effective wind speed is 0.7 x 25 = 17.5, say, 18 kn. This is plotted inside the station circle.

Plot II indicates:
a. Surface wind of 33 kn from 320° true.
b. The wind waves have a period of 7 seconds and significant height of 12 feet.
c. The swell is of height 20 feet, from the same direction as the wind, and has a period of 9 seconds.
d. Barometer: 1010.9 mb. Tendency: 2.0 mb, falling.
e. Air temperature: 5 °C. Dew point temperature: 0 °C. Sea surface temperature; 9.0 °C.

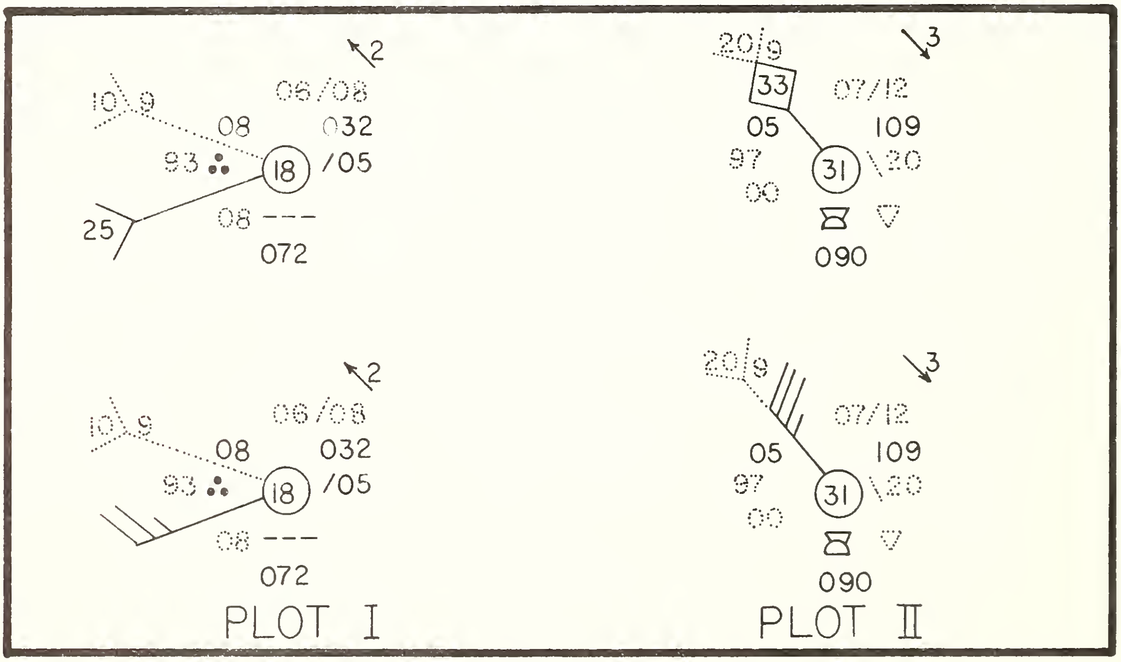

Figure 9 — Modified plotting models for synoptic observations from ships. Dotted lines and figures are in red. The models in the bottom row use wind barbs instead of the exact reported wind speed used in the top row. For operational use on hand-plotted charts, it has been found that the barbed model has a higher visual impact than the barbless one, and, in fact, still yields effective wind values within about two knots of the more exact barbless model. (Two fine-tipped felt pens, one black and the other red, taped side by side together, makes plotting in two colors very easy. Items plotted in red are: wind wave period/height; swell direction, height, period; visibility; dew point temperature; past weather; falling barometric tendencies.)

f. Present weather: not of any significance, so was not plotted.
g. Low cloud type: cumulonimbus. Past weather: showers.
h. The heading of the ship is SE at 11-15 kn (code figure 3).

The atmosphere is unstable, and the air mass/sea surface temperature classification is 1. The effective wind speed is 0.95 x 33 = 31.35, say, 31 kn. It should be noted that it is often difficult on a ship to discern between wind waves and swell when they are coming from the same direction as in this report. Most likely, the waves were wind waves of 20 feet since the periods reported are fairly short for a swell of 20 feet.

5.8 Procedure for analyzing the effective wind field chart. The following procedure is suggested for drawing isopleths of the effective wind values:

(1) A routine surface analysis is first carried out on the plotted chart delineating warm, cold, and occluded fronts as accurately as possible. Particular attention should be given to the spacing of the isobars. The degree of smoothing exercised is a matter demanding care and experience, and the only guidance which can be offered is that best results will normally be obtained from the best fit of the isobars to the observations and the fronts. Whenever possible, satellite pictures should be used to obtain accurate frontal analyses. Drawing some streamlines is often helpful.

(2) The areas where the cyclostrophic effects could be important should next be considered and conversions made to gradient wind values where necessary.

(3) The characteristics of the air masses involved should next be evaluated, (*e.g.*, pre-warm frontal, warm sector, post-cold frontal, and so on). Particular attention should be given to offshore flow of arctic air masses from ice-covered surfaces. By considering sea surface temperatures either from reports from ships or from a sea surface temperature map, values of $(T_S - T_A)$ should be estimated at selected points where geostrophic winds can best be measured. Whenever possible, ship reports, which are plotted on the chart in the above manner, are used to classify the atmosphere according to the definitions of air mass/SST classification defined in Section 5.6 and Table 7.

(4) Having defined the air mass/SST classification, use the ratios given in Table 7 to convert gradient winds into effective winds at surface level. This procedures is essential when using prognostic charts.

(5) Shipping reports must be used as fully as possible, particularly in very stable conditions when the geostrophic wind can be quite unrepresentative of conditions at sea surface where the air mass is exercising little or no bite on the surface. Particular care needs to be taken in areas where sea fog or low visibility is reported.

(6) Isopleths are generally drawn on the charts at five knot intervals starting with 20 knots (20, 25, 30, 35, etc.). Values below 20 knots need not be considered since they have little effect on raising the swell.

5.9 Example of straight isobar situation. In illustration of the point made in paragraph 5.3 (a), an analysis of a devastating storm that affected the coast of British Columbia on 29-30 March 1975 is instructive. Damage to the value of many millions of dollars was caused to shipping and coastal installations by that storm, and several small craft were sunk in the inland waterways. The full synoptic sequence of events will not be given, but it is

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Ed. note: The complete W.M.O. code for plotting synoptic observations from ships can be found in **Federal Meteorological Handbook No. 2 - Synoptic Codes.**

TABLE 7

MULTIPLICATION FACTORS TO APPLY TO GRADIENT WIND VALUES

Type	Atmospheric Description	Satellite Pictures	$T_{sea} - T_{air}$	Multiplication Factors
1	Very unstable	Cloud sheets	Greater than 4 °C	0.95
2	Unstable	Cell clusters	Between 2 °C & 4 °C	0.90
3	Average	Stratus	Small but positive	0.80
4	Stable	Surface obscured by cloud	Small but negative	.7 in strong wind .6 in light wind
5	Very stable	Low fog or stratus	Negative & more than 1.5 °C	.6 in strong wind .5 in light wind

easy to understand how the freak circumstances arise from a consideration of the synoptic chart for 1200 GMT for that day (see Figure 10).

The major feature of the chart is the intense high pressure over the Gulf of Alaska having a central pressure of 1040 millibars. In association with this high pressure system, a complex depression to the eastward must be considered. This had formed over eastern Alaska on 28 March and moved rapidly southeastwards parallel to the mountain chain of eastern British Columbia. It resulted in the formation of an elongated trough of low pressure lying over the mountains with its axis parallel to the coast. In mountainous areas, low pressure systems are generally complex and it is often possible to identify more than one center. Note the close similarity of the synoptic situation with Example IV quoted at the end of Chapter 6. The elongation of the trough results in a tight straight isobar situation on the western flank of the the trough giving rise to a northwesterly air stream, covering a fetch of several hundreds of miles. Very often, cold frontal conditions or squall lines can be identified in the air stream. In the case under consideration, the effect was almost certainly enhanced by some katabatic wind flow down the mountain valleys of eastern Alaska and British Columbia, for many reports were received of winds exceeding 100 knots in the inland waterways.

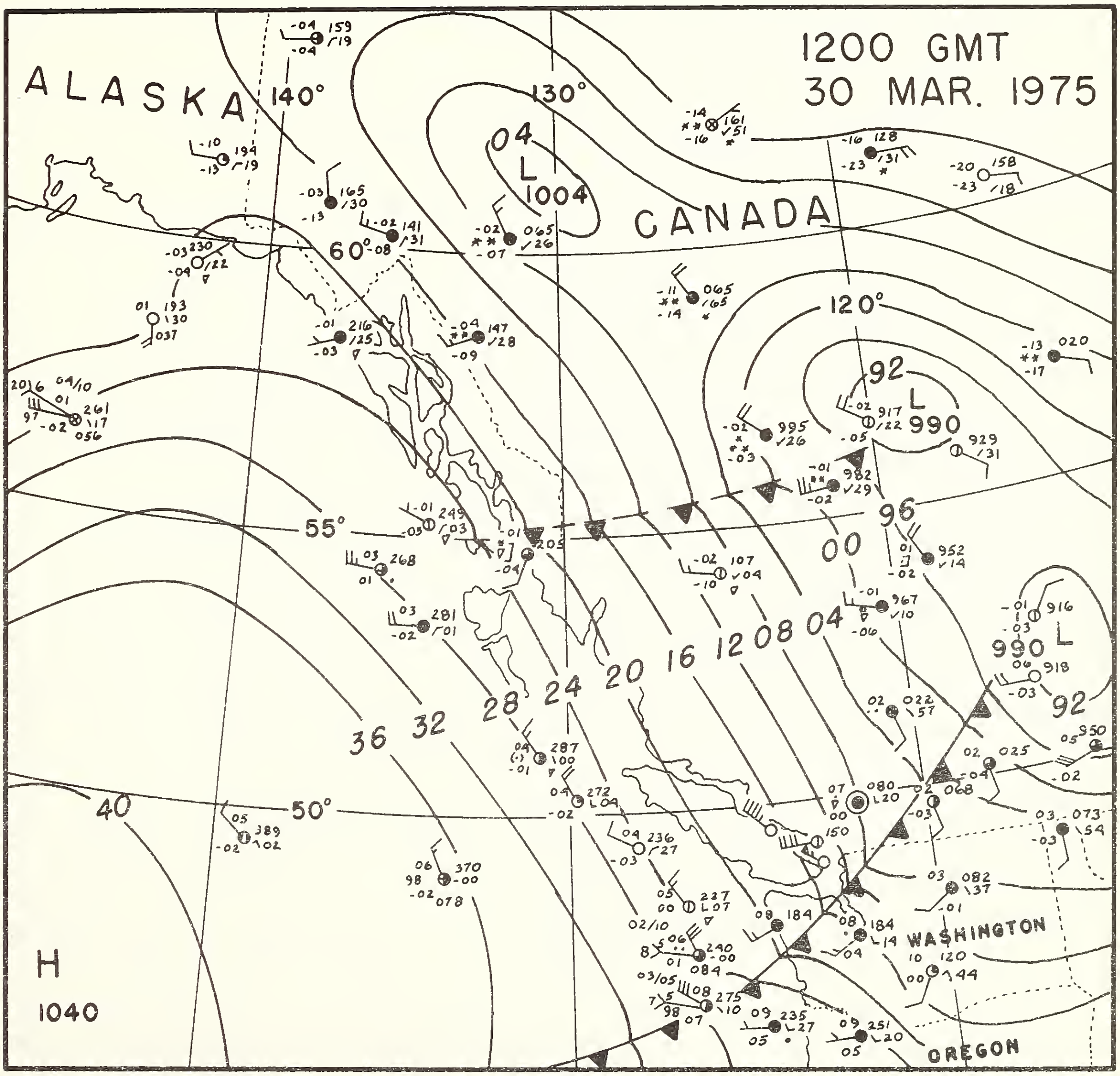

Figure 10 - Synoptic chart for 1200 GMT 30 March 1975.

CHAPTER

6

DESTRUCTIVE WAVES AND THEIR CAUSES

6.1 Introduction. In Chapter 2, some graphic descriptions were given of ''freak'' or ''killer'' waves and of ''holes'' in the ocean. The heights of waves given in these accounts were all estimates and therefore subject to speculation.

A ship is seldom on an even keel when wave observations are made from known heights of decks, bridges, or masts and are naturally open to question when there is considerable movement. How correct were such estimates and how justified is it to label the circumstances as ''freak?'' Of greater consequence are the questions, ''How often do they occur?'', ''Where are they likely to be encountered?'', ''Can forewarning or avoiding action be taken?''

It is now possible to measure wave heights with wavemeters mounted in weather ships and buoys. The latest evidence suggests that seamen's estimations have been good and that ''freak'' occurrences are not infrequent in certain ocean regions.

It is this latter point that is causing the shipping community to take such tales of ''freak waves'' and ''holes'' in the ocean very seriously, and it is equally important for national weather services to do so and hindcast such events in order that rules for forecasting them may be developed. It is of even greater importance that seamen understand how it is they arise and the whereabouts they are most likely to be encountered. They should also know what seamen like precautions they should take to defend themselves against them, for the impact of such waves on a ship depends much on her speed and how she is handled in the circumstances.

6.2 The effects of bottom topography. In the graphic description of giant swells quoted in Chapter 2 from Commander Worsley's book, *Shackleton's Boat Journey,* the author refers to the impact of large swells on subsurface sills or reefs and in particular the Agulhas Bank off South Africa and the Birdwood Bank near Cape Horn. It is from the vicinity of such major sills at comparitively shallow depths that the most striking accounts have come of ''solid walls'' of water which have impacted on ships. There is no question that bottom topography is one of the causes, and ships are generally wise to avoid the close vicinity of a sill in coastal waters bordering on a major ocean.

It is interesting to consider the theoretical aspects of the depth to which such swells penetrate retaining sensible amplitudes. Let us assume a swell of amplitude 40 feet and wave length 3,000 feet, which is the approximate order of magnitude of the swells described. In deep water, the amplitude decreases exponentially according to the formula (see Appendix A):

$$r = Ae^{-2\pi d/L}$$

At a depth of 50 fathoms (300 feet) the ratio $d/L = 1/10$ corresponds to a value of 0.53 for the exponential factor $e^{-2\pi d/L}$ (Table A-1, Appendix A). Hence, the particles of water at this depth are describing circular orbits

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Ed. note: A very dramatic and well-illustrated article about freak waves appeared in **Smithsonian** *magazine. Peter Britton (no relation to G.P. Britton), ''Nightmare Waves Are All too Real to Deepwater Sailors,''* **Smithsonian,** *February 1978, p. 60.*

of radius 20 feet. At a depth of 100 fathoms (600 feet) the ratio d/L = 1/20 corresponds to a value of 0.28 and gives an amplitude of 11.2 feet.

The study of a navigational chart will indicate areas where the depth changes rapidly. The impact of internal waves on such underwater sills or breakwaters will cause some disturbances to extend up to the surface. An example of internal waves created by a sill is given in Chapter 9, but surface wave forms arising from internal waves in the ocean are encountered in many oceans.

The areas where such internal disturbances are likely to have some consequence at surface level will be on the eastern sides of the major oceans since a fetch of several hundreds of miles exists to the westwards sufficient to create swells of maximum wave length and having considerable water movement at depth. From the technical viewpoint, it is important to know if the circumstances can arise from a chance combination of waves of various amplitudes or whether it is necessary to have some internal influence in the sea caused by the waves impacting on a sill. Alternatively, they may be due to strong currents, perhaps influenced by bottom topography. Some ships, although well equipped, have almost certainly had no opportunity to get out a MAYDAY signal and have gone to the bottom with the crew largely off guard.

6.3 Chances of unusual occurrences. Theoretical considerations, supported by some observed facts, show that one wave in 23 is twice the height of the average wave; one in 1,175 cases exceeds it by three times; and one in over 300,000 exceeds four times the average height. If we assume an average period of ten seconds for the waves, it can be seen that a wave of twice average height may be expected every 4 minutes, one three times average height may be expected every 3 hours, and one of four times average height once every 60 days. In placing such figures into perspective, it should be remembered that the wind stress is generally changing continuously in direction and intensity and the chances of such happenings are slight.

In these circumstances it is not difficult to understand why it is possible for very high amplitude waves to occur with some frequency in the southern oceans, although it is very doubtful if the swells actually encompass the globe as described in Section 2.12 quoting from Commander Worsley's text.

The movement of depressions over the southern oceans is seldom exactly west-east, and it is unlikely that swells do actually encircle the globe as is suggested. Nevertheless, the length of fetch is normally more than sufficient to create fully developed seas. Depressions in the southern oceans are most frequently born on antarctic fronts in the southwestern regions of the great subtropical anticyclones. As they develop, the centers initially move southeastwards; the track becoming more easterly as the depressions approach the ice edge. Many, if not most of them, cross the ice boundary and then fill. Since either three or four such subtropical anticyclones are normally present on a hemispheric surface chart of the southern oceans, it follows that there are three or more mean tracks followed by the depressions in the respective oceans leading to certain preferred places for storminess near the Antarctic Continent. Captains of whaling vessels have confirmed these regions of preferred storminess.

Equally, we can see that in the trade wind zones, particularly in locations where winds blow strongly towards the equator from colder climes, the chances of high swells are great. It is largely for this reason that sea passages in the trade wind zones are not always pleasant experiences. The air mass is often relatively colder than the sea surface temperature, and hence, the degree of bite of the wind on the water is high; also the fetch extends over several hundred miles in a sensibly constant direction.

One of the world's roughest ocean crossings is the route between Aden and Ceylon during the summer months of June to September at the height of the southwest monsoon. Ships emerging from the lee of the island of Socotra experience the full impact on the beam created by a 30-knot wind with a long fetch. Correspondingly, at the height of the northeast monsoon six months later, the effect is much the same; although the wind speed is appreciably less, the bite of the cold air on the water is greater. The swells are high, and the chances of encountering unusual combinations of large waves is greater for the reasons given above.

Such high waves are therefore isolated events brought about by the chance combinations of smaller ones in the same trains. Hence, it is hardly justified to designate such combinations as "freaks." Without seeking to detract from their grandeur or destructive capability it is believed that seamen and forecasters must appreciate that they could be encountered at any time by chance in a fully arisen sea.

6.4 Physical explanation for "holes". It seems unlikely that such simple combinations of waves alone give rise to holes, and another physical explanation should be sought. Surfboard enthusiasts know only too well the effects of riding a wave which turns out to be a "dumper." Under certain circumstances, an outflowing undertow affects the flow at the base of the wave, and the luckless surf rider is pitched forward on to his nose on the sand and rolled over by the impetus of the wave he is riding. It is equally possible that "holes" in the ocean are created by some similar type of undercurrent arising perhaps from water accumulation on a subsurface shelf or sill. Such back flow would cause waves to rear up and present the appearance of solid walls of water.

This explanation may not be entirely adequate, and "holes" might equally be created in the open ocean by a major change of wind direction associated with a frontal passage or equally by current flow.

"Holes," such as described by Commander I.R. Johnston, R.N., have been reported many times off the Cape Coast of South Africa. Although Drake in his voyage around the world described it as the "fairest Cape in all the world," seamen have more rightly called it the Cape of Storms. The major cause of storminess is the contention of wind against current, since a strong southwesterly air stream following a coid front (appropriately called a "southerly buster") often raises a short steep sea to oppose the westerly set of the Agulhas Current, which can exceed three knots. The bottom topography exerts a considerable influence on the speed of the current, and it is generally advisable for ships to avoid the area of the sill where the currents are strongest. Certainly, reports of "holes" occurring in the ocean seem to be most frequent in regions of marked sills, such as the Agulhas bank, suggesting that bottom topography ought not to be discounted as a contributing factor or even the principal cause.

6.5 Forecasting "freak" waves and "holes". In dealing with the forecasting problem in coastal waters, the influence of bottom topography and in particular shelves off a rocky shore should be borne in mind. The coasts of Norway, Alaska, British Columbia, South Africa, Portugal, and Iceland are but a few of the hazardous coasts so influenced. A number of ports and harbors, such as Cape Town, experience disconcerting seiche effects as a result of such combinations of sea and swells.

Close to many coasts where there is a large range of tide, a similar effect occurs on a smaller scale, but it is equally devastating to the small ship. An example of such conditions occurs periodically in the harbor at Invergordon on the east coast of Scotland. In certain synoptic circumstances, a southwest wind channels between the highlands of Scotland on either side of the Caledonian Canal to emerge on the east side in a venturi effect at gale force. Sea state conditions in Invergordon in the Loch vary according to the state of the tide. Small boats which are working comfortabley can quickly find themselves in embarrassing situations when the tide turns -the effects of wind against water producing waves which stand up in disconcerting random mushroom effects.

A study of some actual wave recordings made during such events is very necessary and some of the few which are now available will be discussed in more detail.

Example I - Attention is drawn to an informative article by E.H. Schumann and reproduced in the January 1976 (Volume 20, Number 1) of *Mariners Weather Log* published by the U.S. National Oceanic and Atmospheric Administration's Environmental Data and Information Service. Figure 11 shows sections of wave recordings made by a wave recorder mounted in the hull of the research vessel *Meiring Naude* taken when moving in and out of the main stream of the Agulhas Current on 23 June 1971. The interval of time between the recordings was short with the ship drifting under similar conditions while the recordings were being made.

It is interesting to note that waves of different period are amplified to different extents. The author of the article which describes these records, E.H. Schumann of the National Research Institute for Oceanology, Durban, draws attention to the fact that the height of a short period wave (which also has a short wave length) increases proportionately more than the height of a wave with larger period. This cannot go on indefinitely, and so the shorter waves are amplified to breaking point while the larger waves pass through without much change of height. It is a noticeable feature of these waters that the seas are normally very choppy and broken.

Schumann very rightly points out that the steepness of waves is usually of far greater consequence to the mariner than the heights of actual waves and that the apparent steepness of the waves will vary not only with current variations but also with the speed of the ship. This is only one good reason why some interpretation of

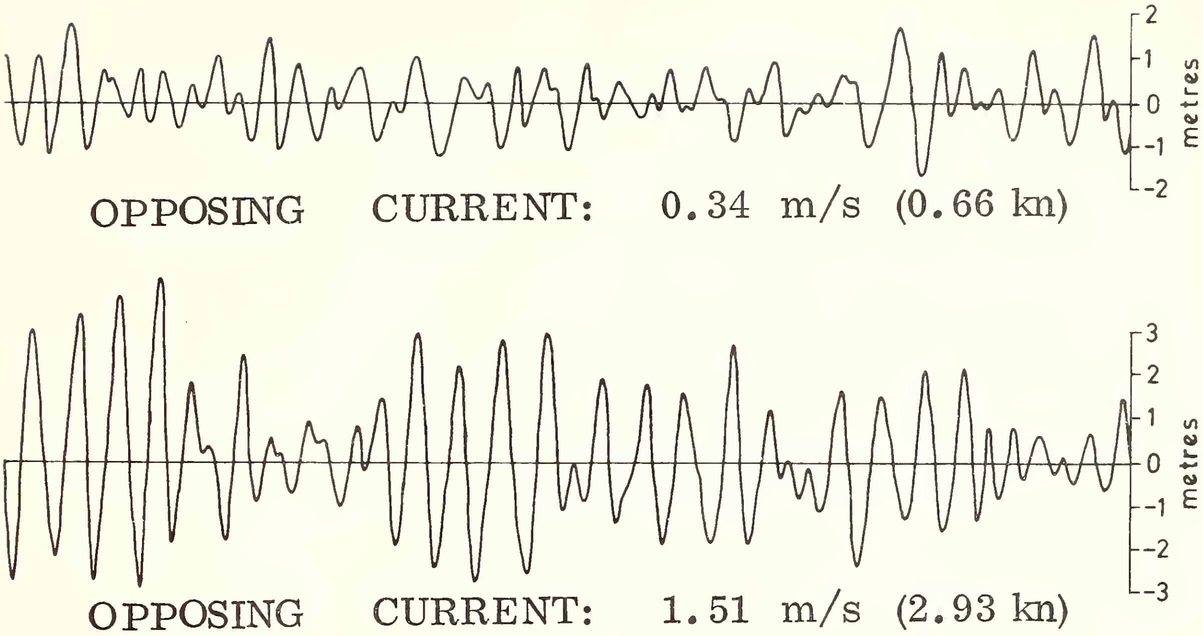

Figure 11 - Wave traces with opposing currents of 0.34 meters/second (0.7 knots approx.) and 1.51 meters/second (3 knots approx.), respectively. (From "High Waves in the Agulhas Current" by E.H. Schumann. *Mariners Weather Log,* January 1976.)

wave data needs to be done on board ship by an experienced officer who is thoroughly conversant with the characteristics of his own vessel in addition to understanding the general problem of wave characteristics in currents.

Example II - A shipborne wave recorder was carried on board the lightship *Daunt,* which experienced a freak wave off Cork about 0300 on 12 January 1969; the maximum wave height being about four times the average. The chances of such occurrences are only 1 in over 300,000 in a normal wave train. Such statistical factors assume that no unusual cause arose, such as a strong current or tide setting in to cause the freak wave. A copy of the trace is shown in Figure 12.

The actual height of this wave was about 42 feet at a time when the significant height was only 16.5 feet. It is worth considering the weather situation for the time on that day to see if there was anything unusual to cause such a freak wave. From 1200 on 11 January to 0300 on 12 January (the time of the recording) a fresh east-southeasterly to easterly air stream covered the area. The observations from Southern Ireland and from ships on passage to the south show a steady wind flow of about 30 knots associated with a fairly deep, but slow moving, depression centered 300 miles to the west-southwest. It does not seem that there was any marked contrary current or tidal flow; the occurrence being closer to tidal neaps than to springs. However, the meteorological analyses do indicate that a front associated with the depression passed the position about the time the wave was recorded and that the wind probably veered through 90° or perhaps more. The conclusion is that the tidal effect was not responsible, but that a fairly rapid wind shift may have had some influence by creating a cross sea to the swell.

Example III - Dr. Laurie Draper of the Institute of Oceanographic Services, Wormley, England, has made a study of waves over many years and particularly of the recordings at the ocean weather stations, which frequently have had wave meters in service since 1961. Dr. Draper is an acknowledged expert on waves, and he be-

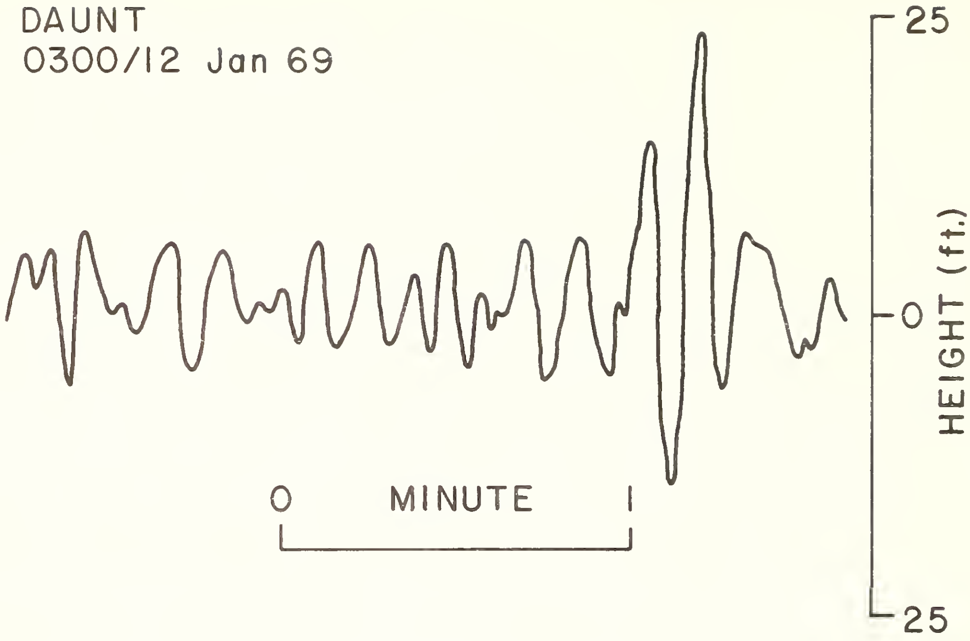

Figure 12 - Wave recorder trace taken on lightship *Daunt* off Cork.

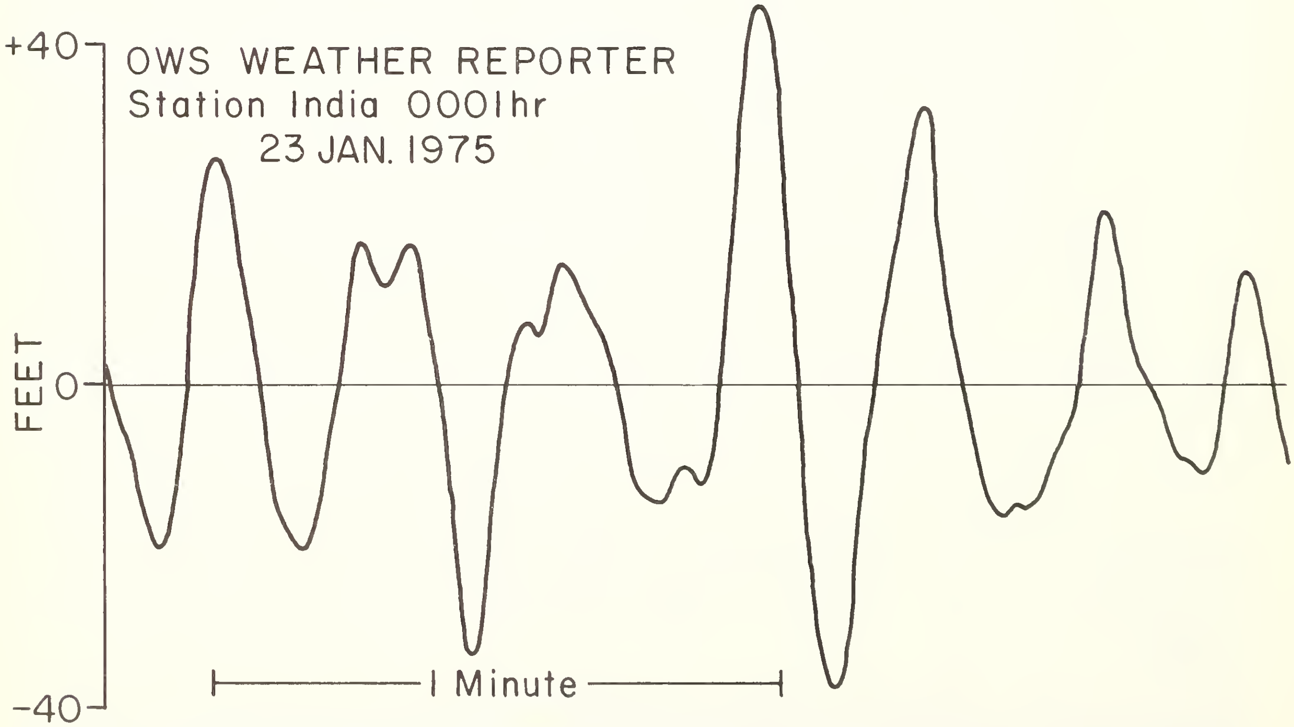

Figure 13 - Ocean Weather Station INDIA wave record 23 January 1975. (From ''Freak Ocean Waves'' by L. Draper, *NOAA Pacific Newsletter,* March 1976).

lieves that the highest measured wave was one of 83 feet from crest to trough recorded on 23 January 1975 at Ocean Weather INDIA (59 °N 20 °W). The wave trace (Figure 13) is reproduced below, and shows clearly a regular swell of period about 15 seconds, rising to a maximum amplitude and then decaying almost according to textbook theory. Is it justified to consider such a wave as a "freak" or did it occur normally as a result of a combination of wave fields and was to be expected from statistical theory?

A study of the synoptic conditions which gave birth to this giant wave is instructive, particularly as weather observations were being recorded every hour with estimations made by the observers of sea and swell; although (quite understandably) these were not always attempted at night in this very severe gale. Over the same period, similar observations were being carried out at Ocean Weather Station JULIET (52.5 °N 20 °W) where conditions were generally very similar. Indeed, from some theoretical considerations, higher waves could have been expected at OWS JULIET than at OWS INDIA.

The synoptic situation for 1200 GMT on 22 January is shown in Figure 14, and comparable hourly data from the two ships are listed in Table 8. A long westerly fetch with a tight pressure gradient prevailed for over 30 hours at JULIET and for 24 hours at INDIA. The center of an intense deepening low of 972 millibars at 61 °N 39 °W at 1200 GMT on 21 January moved slightly south of east to pass close by INDIA in the early hours of 22 January. The central pressure fell to 950 millibars, and an intense pressure gradient then covered the whole belt of latitude between 50 °N and 60 °N, embracing both vessels. Initially, the winds at INDIA were from the southeast quadrant, and they did not reach full gale force until 0100 22 January, some 7 hours later than the onset of full gale conditions at JULIET. Higher wind speeds were generally recorded at JULIET than at INDIA. The hourly graphs of wind speed and the observed heights of sea and swell are shown plotted in Figures 15 and 16. It was during the second wind increase at about midnight on 22-23 January that the highest wave was recorded. This appears to be consistent with the gradual build-up of the swell from the west.

It is of interest to speculate why the swell was finally higher at INDIA than at JULIET, but a consideration of the air densities (see Table 8) is instructive. The density of the air mass was generally higher at JULIET, but the values of (ϱa — ϱs) were greater at INDIA; an indication that the air mas had a better bite on the water surface at the INDIA station throughout the period.

Example IV- On 2 January 1977, the buoy EB 21, positioned at 46 °N 131 °W, flipped over in a strong gale. The buoy reported normally up to 1200 GMT on that day, but no report was received at 1500 GMT or subsequently; hence, the time of occurrence was known to within three hours. When the buoy was recovered, the mooring was still attached and virtually no free water was found inside the buoy (after towing into harbor). The only damage appeared to be to the sensors on the buoy itself.

Everything points, therefore, to the conclusion that this stable buoy, although restrained by its moorings, was flipped over by steep, heavy seas. Since a fair amount of reliable data were available, including spectral data from the buoy itself up to 1200 GMT/2 January, it is useful to examine the meteorological circumstances in more detail. The synoptic circumstances, typical for that day, are shown in Figure 17. Similarity is immediately obvious with the chart situation depicted in Figure 14 in the North Atlantic, insofar as there are two low centers, some 300 miles apart, with the rear one tending to catch-up and merge with the leading one to form one single center. In consequence, on the western side of these twin disturbances, a "straight-isobar" situation arose and was maintained for several hours. Furthermore, it was one in which a cold front or more particularly, a polar front appeared to be entrained.

All the ingredients were present for a rapid increase in sea state: an accelerating wind force, a straight-isobar formation orientated northwest towards the southeast, and an advancing polar front with a high density air mass bearing down on the buoy. The significant wave height values at the buoy for that day were: 0000GMT (15 feet); 0300 (16 feet); 0600 (18 feet); 0900 (20 feet); 1200 (23 feet); 1500 (no report). The last reported value was not in itself phenomenonally high, but it was obviously of the order of 25-30 feet. Temperatures reported by the buoy were as follows on that day: 0000 GMT (+09 °C); 0300 (+08 °C); 0600 (+08 °C); 0900 (+08 °C); 1200 (+05 °C), the latter being a significant fall after the arrival of the cold front and over 6 °C lower than the sea temperature. The sea surface temperature was constant throughout the day at 11.5 °C. It seems highly probable, therefore, that the buoy flipped over about the time of arrival or soon after the cold or polar front passed by.

TABLE 8

COMPARATIVE VALUES OF IMPORTANT ENVIRONMENTAL FACTORS AT OCEAN WEATHER STATIONS JULIET (J) AND INDIA (I) 21-23 JANUARY 1975

Date Time(GMT)	Wind Direction-Speed(kn)		Sea Temp. (°C)		Air Temp. (°C)		Dew Point (°C)		Surface Pressure (mb)		Air Density (kg/m³)		$\rho_a - \rho_s$	
21 Jan	J	I	J	I	J	I	J	I	J	I	J	I	J	I
06	250-28	170-12	9.6	8.6	10.0	5.7	9.6	-2.0	1014.7	1005.3	1.244	1.264	+.001	+.027
09	260-20	150-20	9.6	8.5	9.9	5.2	9.5	2.8	1014.3	1002.0	1.243	1.252	-.001	.022
12	250-27	150-30	9.7	8.6	10.6	5.7	9.7	4.5	1013.5	998.1	1.240	1.243	-.003	.013
15	240-28	250-17	9.4	8.6	10.5	7.4	10.1	3.7	1008.5	995.4	1.234	1.233	-.004	.007
18	220-37	180-14	9.9	8.6	10.5	7.0	10.1	3.2	1002.9	988.7	1.227	1.228	-.003	.009
21	220-45	160-27	10.1	8.5	10.8	6.3	10.4	4.7	997.9	977.7	1.219	1.216	-.003	.012
22 Jan														
00	240-46	130-23	9.8	8.6	11.0	7.0	10.7	6.6	993.8	961.3	1.212	1.191	-.005	.008
01	250-42	250-33	9.8	8.6	9.8	8.2	9.4	6.7	994.4	959.2	1.219	1.185	0	.004
02	260-40	260-50	9.8	8.5	8.7	6.8	7.3	5.2	995.0	960.2	1.226	1.192	+.006	.010
03	270-44	260-48	9.7	8.6	7.7	5.5	4.5	4.1	995.8	961.0	1.232	1.197	.012	.015
04	270-50	270-50	9.7	8.6	7.5	4.6	4.8	1.0	997.4	961.4	1.235	1.204	.013	.021
05	270-55	270-56	9.5	8.6	3.9	3.1	1.9	1.0	999.6	961.8	1.254	1.211	.028	.027
06	260-48	260-50	9.6	8.6	4.2	1.8	2.8	-2.6	1000.5	964.0	1.253	1.220	.027	.034
07	270-50	260-53	9.6	8.6	3.9	1.0	1.3	-0.7	1002.4	965.8	1.258	1.225	.028	.037
08	260-45	270-47	9.5	8.3	3.8	-0.4	0.0	-2.2	1003.3	966.3	1.260	1.232	.029	.032
09	260-50	270-51	9.4	8.4	4.5	-1.0	0.0	-3.5	1003.1	967.9	1.256	1.238	.026	.048
10	250-50	280-49	9.7	8.5	3.7	-0.8	1.5	-3.0	1003.5	968.1	1.260	1.237	.030	.044
11	260-48	290-45	9.6	8.6	3.5	-1.7	1.7	-2.2	1004.0	968.6	1.262	1.241	.031	.049
12	270-65	270-45	9.5	8.5	4.4	-1.2	2.7	-1.3	1002.3	968.3	1.256	1.238	.026	.045
13	270-52	250-45	9.4	8.5	3.8	-0.1	-0.4	-0.7	1001.6	966.5	1.258	1.231	.028	.040
14	260-53	260-50	9.7	8.6	3.8	-0.1	3.8	-1.3	1001.5	966.2	1.256	1.231	.028	.041
15	260-53	260-40	9.7	8.6	3.8	-1.2	2.0	-4.1	1001.8	966.2	1.257	1.236	.028	.047
16	280-48	270-40	9.9	8.5	4.3	1.9	1.5	-1.8	1002.5	965.1	1.256	1.224	.028	.036
17	280-58	250-35	9.9	8.5	3.3	0.5	1.0	-0.4	1003.0	962.7	1.261	1.223	.031	.038
18	280-45	250-32	9.4	8.6	4.0	2.5	1.5	0.0	1002.8	960.0	1.258	1.211	.027	.030
19	270-43	260-40	9.4	8.6	3.1	3.2	1.6	-0.2	1002.6	959.6	1.257	1.209	.027	.028
20	270-44	270-40	9.4	8.6	4.7	1.9	2.4	-0.9	1003.0	958.7	1.255	1.213	.025	.032
21	260-40	300-36	9.3	8.5	4.9	2.0	2.7	-0.8	1002.6	960.4	1.253	1.214	.023	.032
22	260-42	300-38	9.3	8.5	5.3	2.6	3.3	0.2	1001.6	961.6	1.250	1.214	.021	.029
23	260-40	280-38	9.4	8.5	5.2	2.1	3.0	1.6	1001.6	962.6	1.250	1.216	.021	.030
23 Jan														
00	270-35	270-46	9.4	8.5	5.0	2.8	4.1	1.7	1001.8	961.8	1.252	1.213	.022	.028
03	260-35	260-52	9.3	8.6	6.5	5.0	2.4	4.0	1000.4	957.3	1.243	1.196	.015	.018
06	270-40	360-37	9.4	8.6	5.0	3.0	2.9	1.4	1000.1	965.6	1.250	1.217	.022	.027

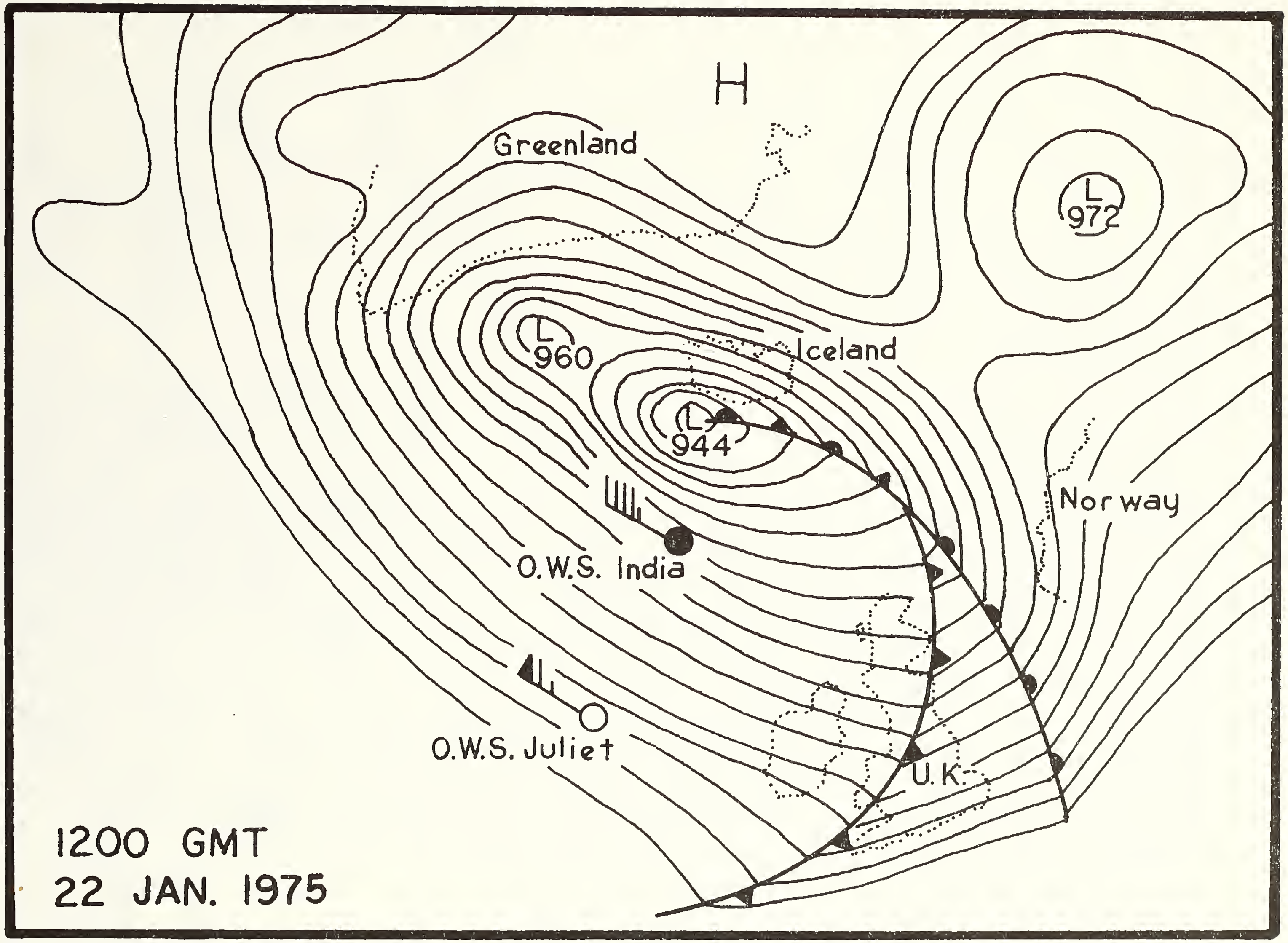

Figure 14 - Synoptic situation 1200 GMT 22 January 1975 Northeast Atlantic.

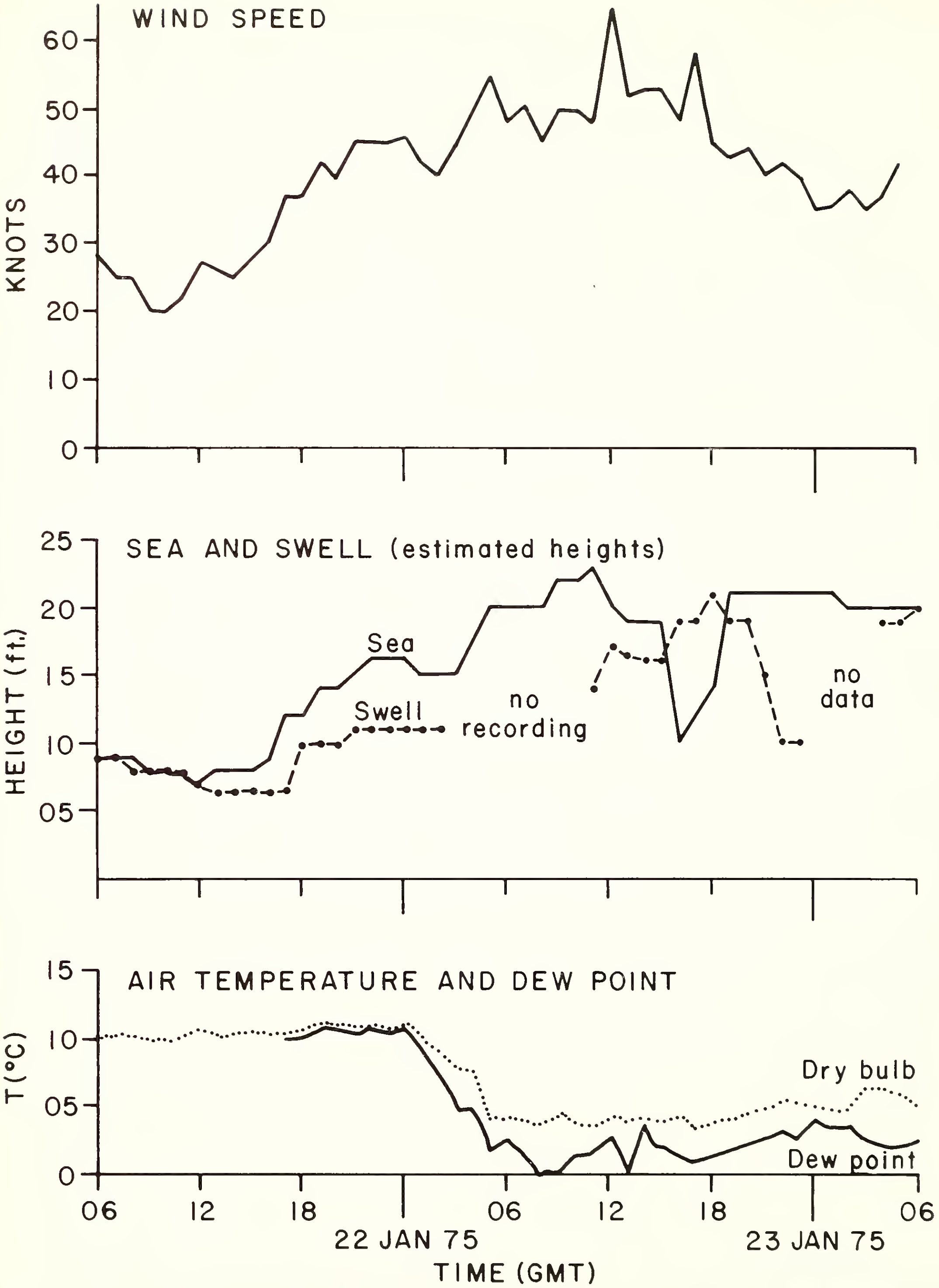

Figure 15 - Ocean Weather Station JULIET 0600/21 to 0600/23 January 1975.

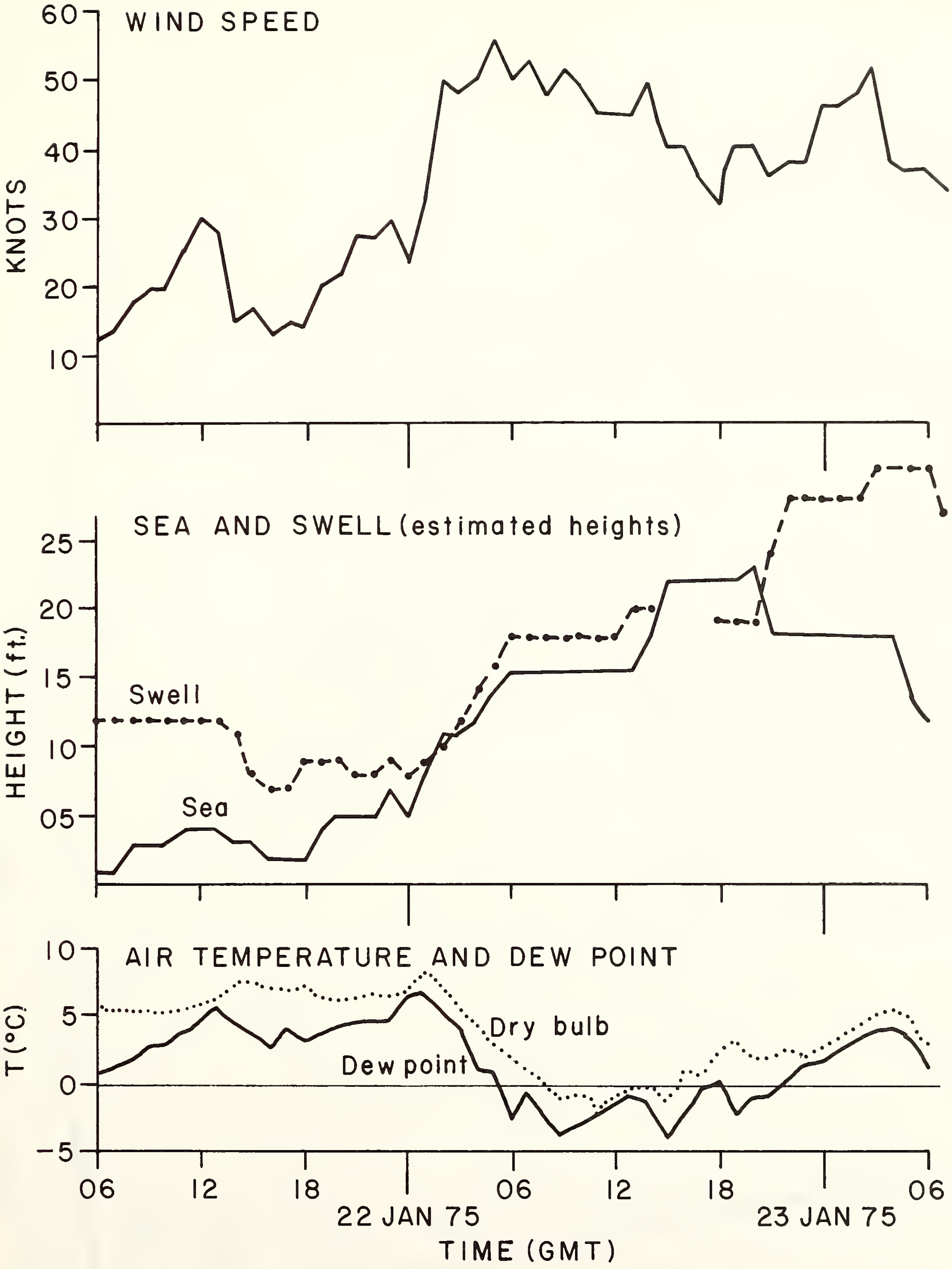

Figure 16 - Ocean Weather Station INDIA 0600/21 to 0600/23 January 1975.

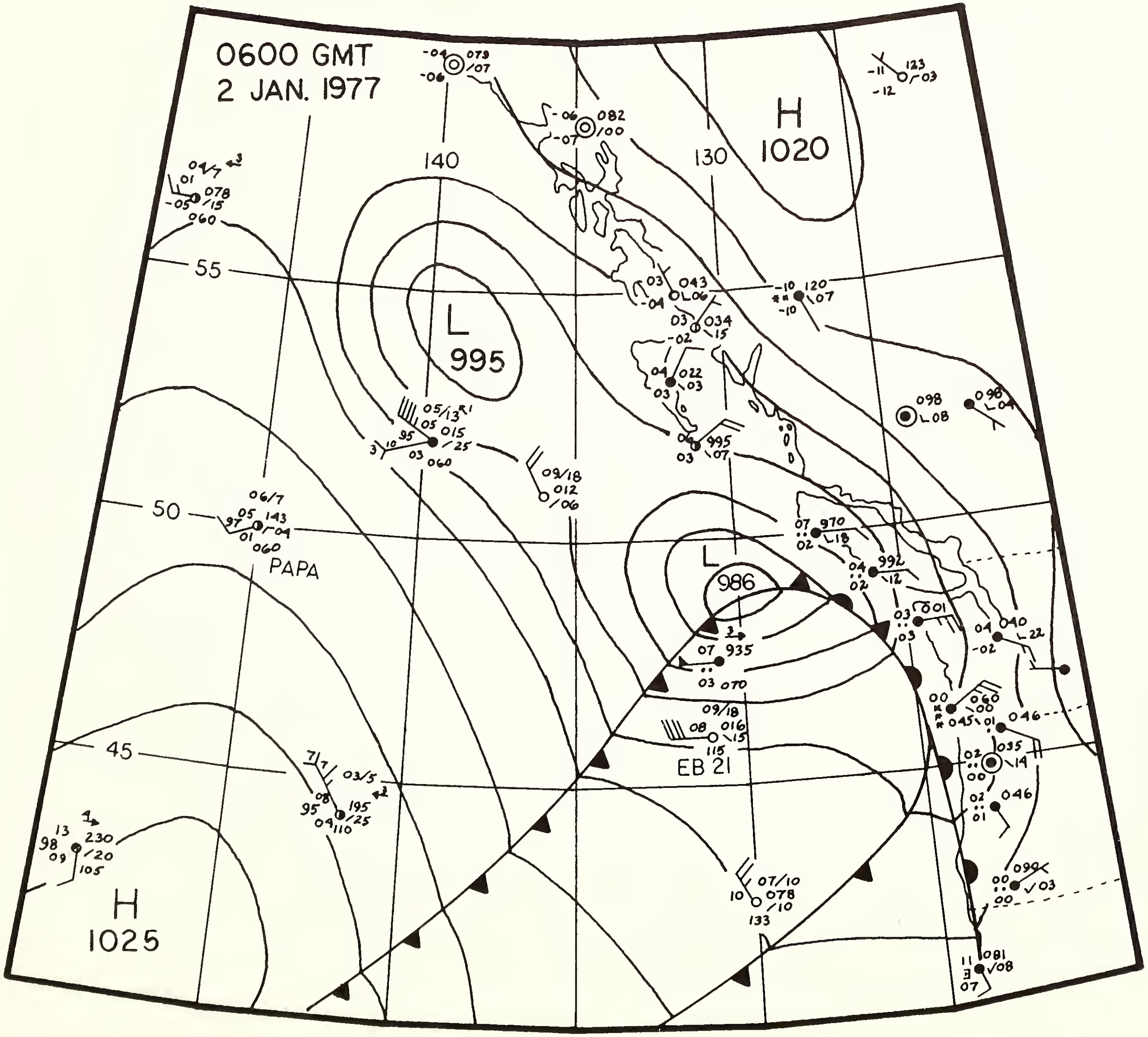

Figure 17 - Synoptic situation 0600 GMT 2 January 1977 Northeast Pacific.

CHAPTER

7

EMPIRICAL FORMULAS AND DIAGRAMS FOR SEA STATE FORECASTING

7.1 Introduction. The theoretical formulas quoted in Appendix A were derived on the assumption that sea and swell constitute a combination of a large number of sinusoidal waves. The theoretical approach can only provide an approximate model to circumstances actually encountered at sea. In practical application for forecasting purposes, it is preferable to use a number of empirical formulas derived from observed measurements and estimates that are embodied in diagrams for convenient use. It should be remembered that none of the graphs predict "freak" wave heights.

A large number of such diagrams exist, computed from known properties of the wind field, such as wind speed, duration and fetch. Almost without exception, such diagrams take no account of the air mass/sea surface temperature characteristics, omitting simple considerations of density variations or currents which are so important for establishing the speed with which seas are raised in adverse circumstances. The work of Darbyshire (and others) showed that the maximum height of waves is usually reached within the first 100 miles of fetch, and this is particularly true when dealing with cold accelerating air masses flowing over seas having a considerably higher temperature. It is exactly such circumstances which create steep breaking seas having short wave lengths that are a menace to shipping.

Hence, such diagrams have limited application and must be used with caution. Nonetheless, they have some importance in dealing with average circumstances and reference to them is desirable. The methods were first worked out by Southens, among others, in England and by Sverdrup and Munk in the United States. The diagrams of Dorrestein, Bretschneider, Neumann, Pierson, Walden and others have also been commonly used in wave forecasting and receive attention in various textbooks and publications.

In order to effect some degree of rationalization among these various diagrams and modifications to them, WMO set up a special committee following the recommendations of the Seminar on Marine Meteorology held in Rome in April 1974. The object was to prepare a manual to state the basic concepts of wave analysis and forecasting, and this has resulted in an excellent publication for general use, *Handbook on Wave Analysis and Forecasting*. Figures 18 and 19 and the examples below are reproduced from this publication and represent the most up-to-date aids of the type mentioned above. They are applicable to open ocean areas and not to semi-closed seas or coastal waters where the waves feel bottom. Figures 18 and 19 are the result of empirical wave measurements in which the characteristic wave height (for practical purposes, the same as significant wave height) can be easily determined by knowing the wind fetch and duration.

Example I: *Figure 18* — $U = 15$ m/sec, $F = 200$ km, $t = 6$ hours. At $U = 15$ m/sec and $F = 200$ km, the diagram gives a corresponding duration of t of more than 6 hours for the sea to become fully developed (12 hours in this case). Thus, the 6 hour wind duration is the limiting factor and not the fetch of 200 km. The

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Ed. note: Although this book is only concerned with sea-state forecasting, there may be occasions when wave height forecasts are needed for inland waters, such as bays, lakes, and so on. Methods for delineating complicated fetch areas and techniques for forecasting waves in very shallow water (to 5 ft. depth) are shown in **Shore Protection Manual - Vol 1**, *by the U.S. Army Coastal Engineering Research Center.*

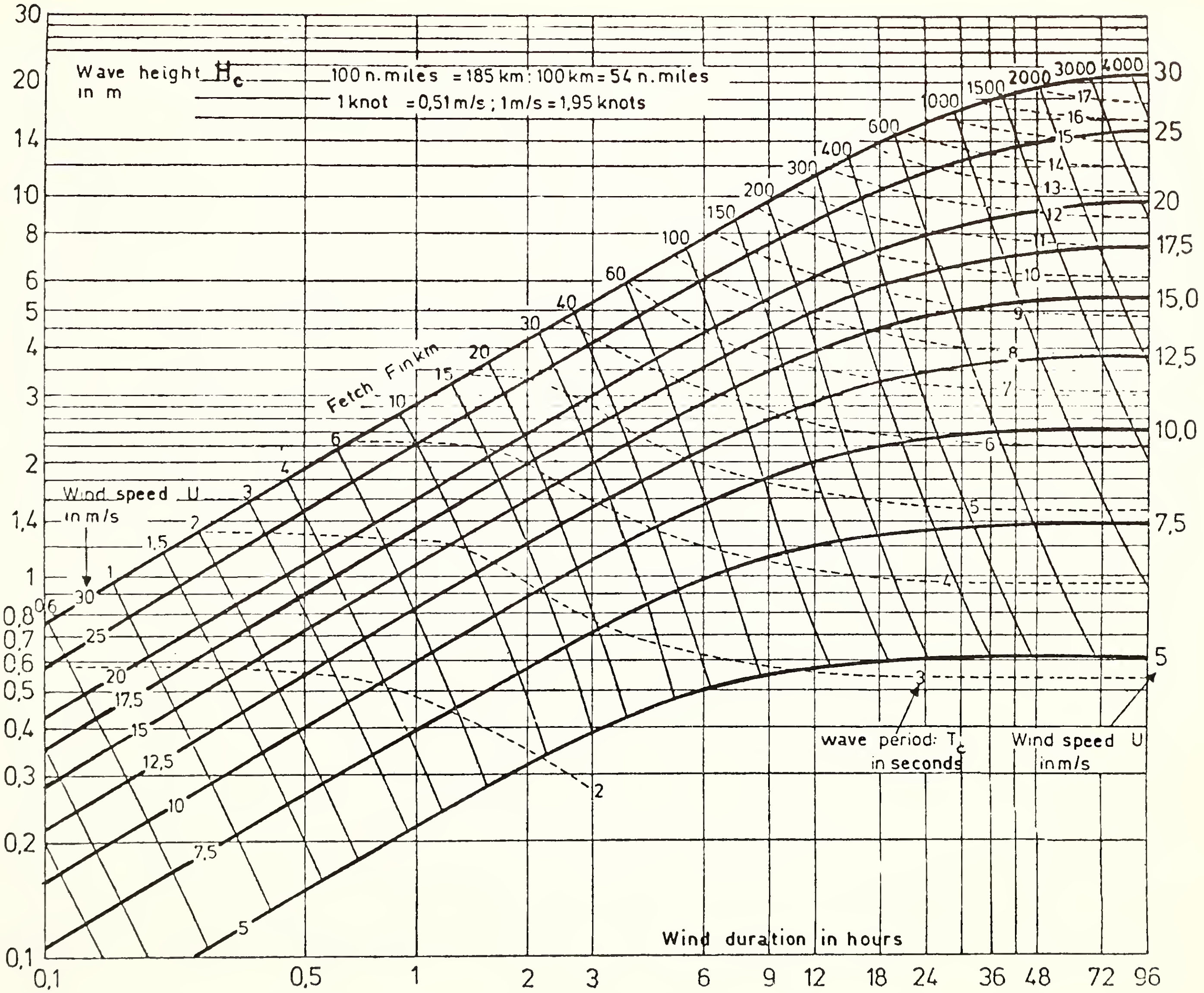

Figure 18 — Wave forecasting diagram - ordinates duration and significant wave height. (From *Handbook on Wave Analysis and Forecasting*. Copyright 1976. Used by permission of World Meteorological Organization.)

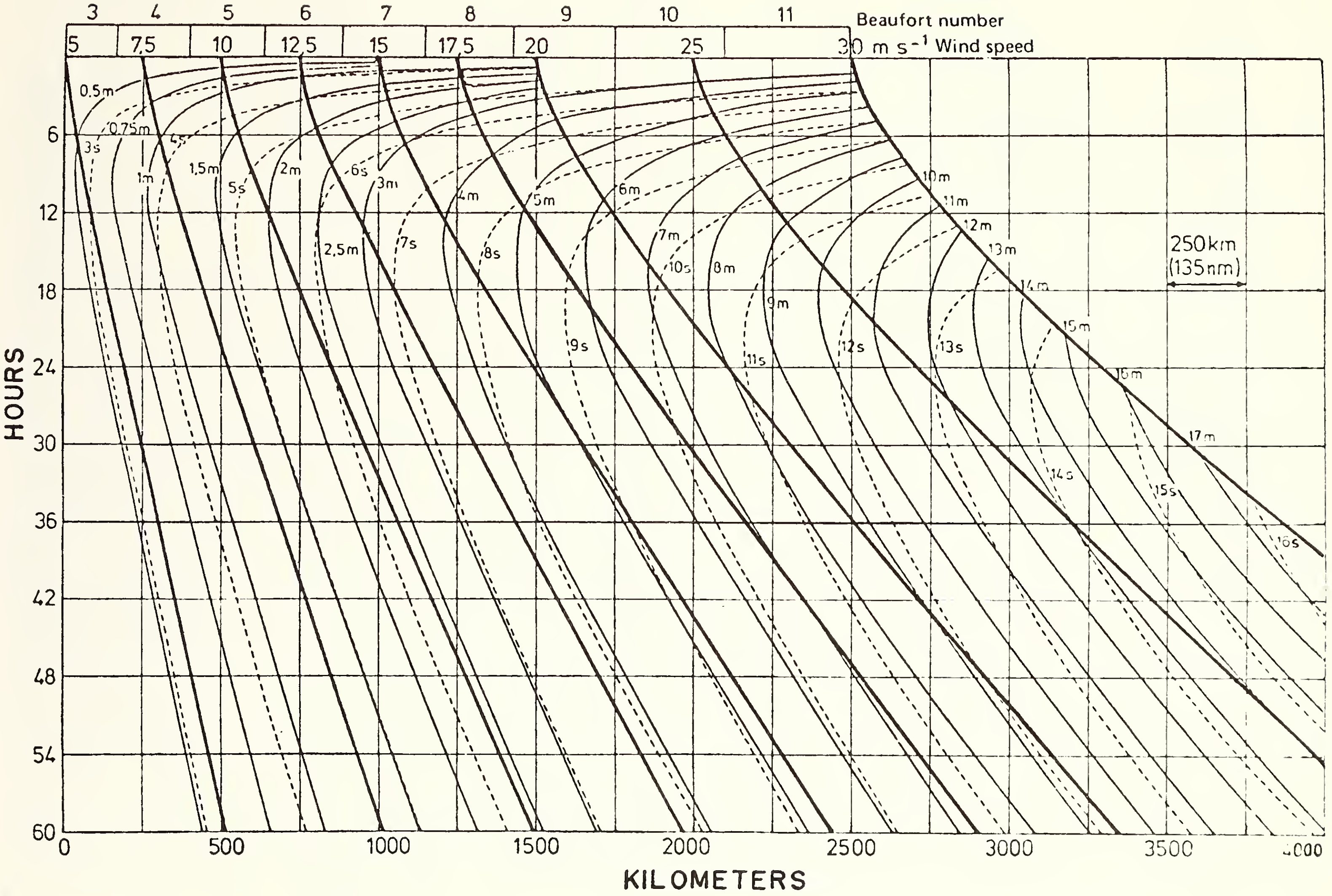

Figure 19 — Wave forecasting diagram - ordinates duration and fetch. (From *Handbook on Wave Analysis and Forecasting*. Copyright 1976. Used by permission of World Meteorological Organization.)

significant wave height is 2.9 m with a period of 5.8 sec.

Example II: *Figure 18* — U = 15 m/sec, F = 200 km, t = 18 hours. The diagram shows that the fetch is now the limiting factor because, at greater fetches, higher waves can be generated when the wind duration is 18 hours. The significant wave height for the 18 hour duration is 4.0 m with a period of 7.3 sec.

Figure 19 is just a variation of Figure 18.

7.2 Diagrams for coastal waters. An empirical approach based on the measurements made of wave heights and periods by wave meters in Lough Neagh in Northern Ireland and at lightships in the North Sea off the coast of East Anglia resulted in the development of a graphical technique for forecasting wave height and period by M. Darbyshire and L. Draper. Five figures are reproduced based upon this work which can be considered to apply more generally to the semi-closed seas or to fixed positions on continental shelves. Again attention is drawn to the fact that no allowance is made for rapidly developing seas under adverse meteorological circumstances, and this is particularly important in the North Sea where steep seas are created very suddenly by north and northwesterly winds. The graphs are shown in Figures 20-24.

The units of wave height are feet. To use the wave height graphs most effectively it is first necessary to determine:

(a) The wind speed in knots.
(b) The fetch in nautical miles.
(c) The wind duration in hours.

The fetch in nautical miles will depend on the wind direction and its variation with time and the curvature of path along the line of fetch from the coast to the ship. As far as possible, actual measurements of estimates of wind speeds by ships should be used, but if the wind is deduced from synoptic charts, the recommended procedure for obtaining the corrected wind speed at surface level should be followed to obtain first the gradient and then the effective wind.

Enter the appropriate wave height graph on the U axis (for coastal or oceanic waters) with wind speed. Using a ruler, follow the line horizontally until it meets either of the constraint lines for fetch or duration (use whichever one is encountered first). Read off the wave height as appropriate.

Example III: Figure 20 - Suppose a ship is 33 miles from shore and has experienced a 40 knot wind for about 6 hours. The horizontal line through the point **0** (40 knots) meets the vertical line corresponding to the 33 mile fetch at point **A** before it meets the curved line representing duration of 6 hours at **B**.

The principal constraint is therefore the limited fetch giving a maximum wave height of 18 feet. Had the ship been 100 miles offshore (for the same wind direction), the 6 hour duration would have imposed a limit of 25 feet on the wave height. Had the 40 knot wind been blowing for only 2 hours as opposed to 6 hours, the wave height would have been 14 feet. This maximum wave height can be multiplied by 2/3 to arrive at an estimate of significant wave height.

Using Figure 22 in a similar fashion, it is seen that when the principal constraint is the 33 mile fetch the wave period is nine seconds, but with a fetch of more than 100 miles, the duration of 6 hours becomes the main constraint, and the period is then 10.5 seconds.

Figure 23 is used in the same manner as Figure 22 when the depth is between 100 and 150 feet. Figure 24 shows how the period of a wave having a given wave length changes as the water shoals. For example, a wave having a 300 ft. wave length and period 7.8 sec. in 600 ft. of water will have a period of 10.5 sec. in 30 ft. of water. Conversely, the graph can be used to determine the wave length if the period of the wave and the depth

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Ed. note: Techniques for delineating a fetch area can be found in WMO No. 446 publication, **Handbook on Wave Analysis and Forecasting.**

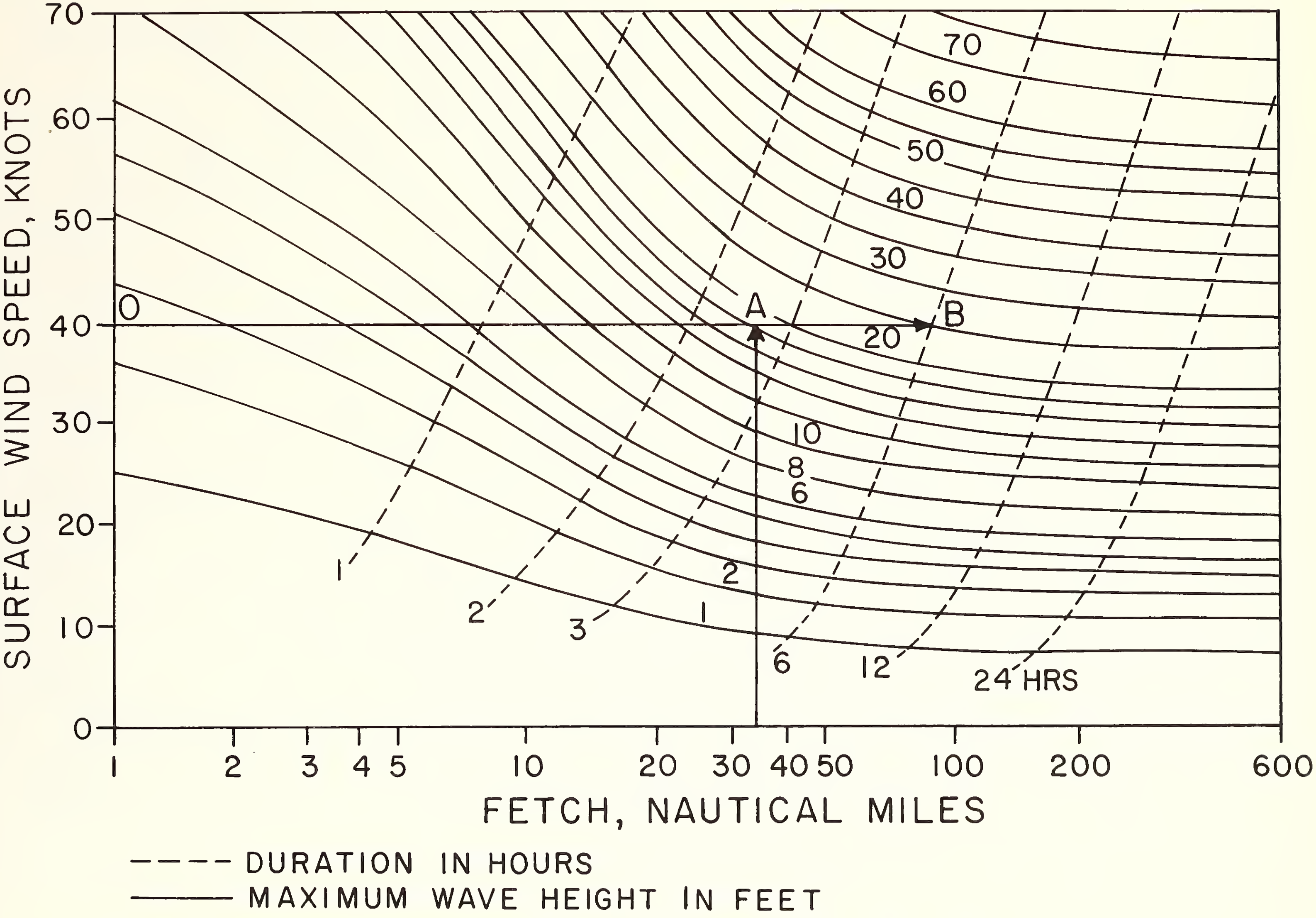

Figure 20 - Graph relating wind speed to maximum wave height with constraints of duration and fetch -oceanic waters.

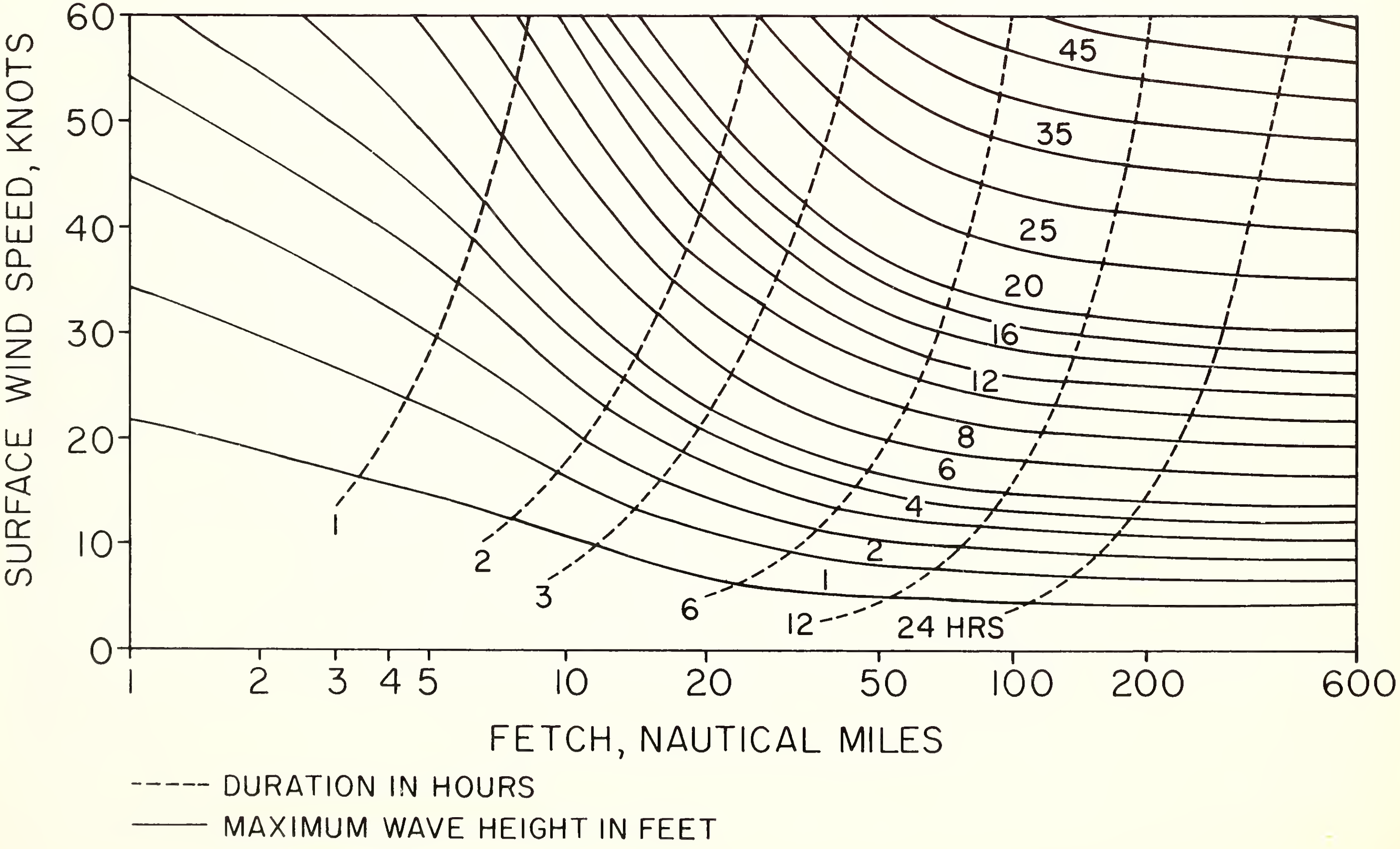

Figure 21 - Graph relating wind speed to maximum wave height with constraints of duration and fetch -coastal waters (depth 100-150 ft.).

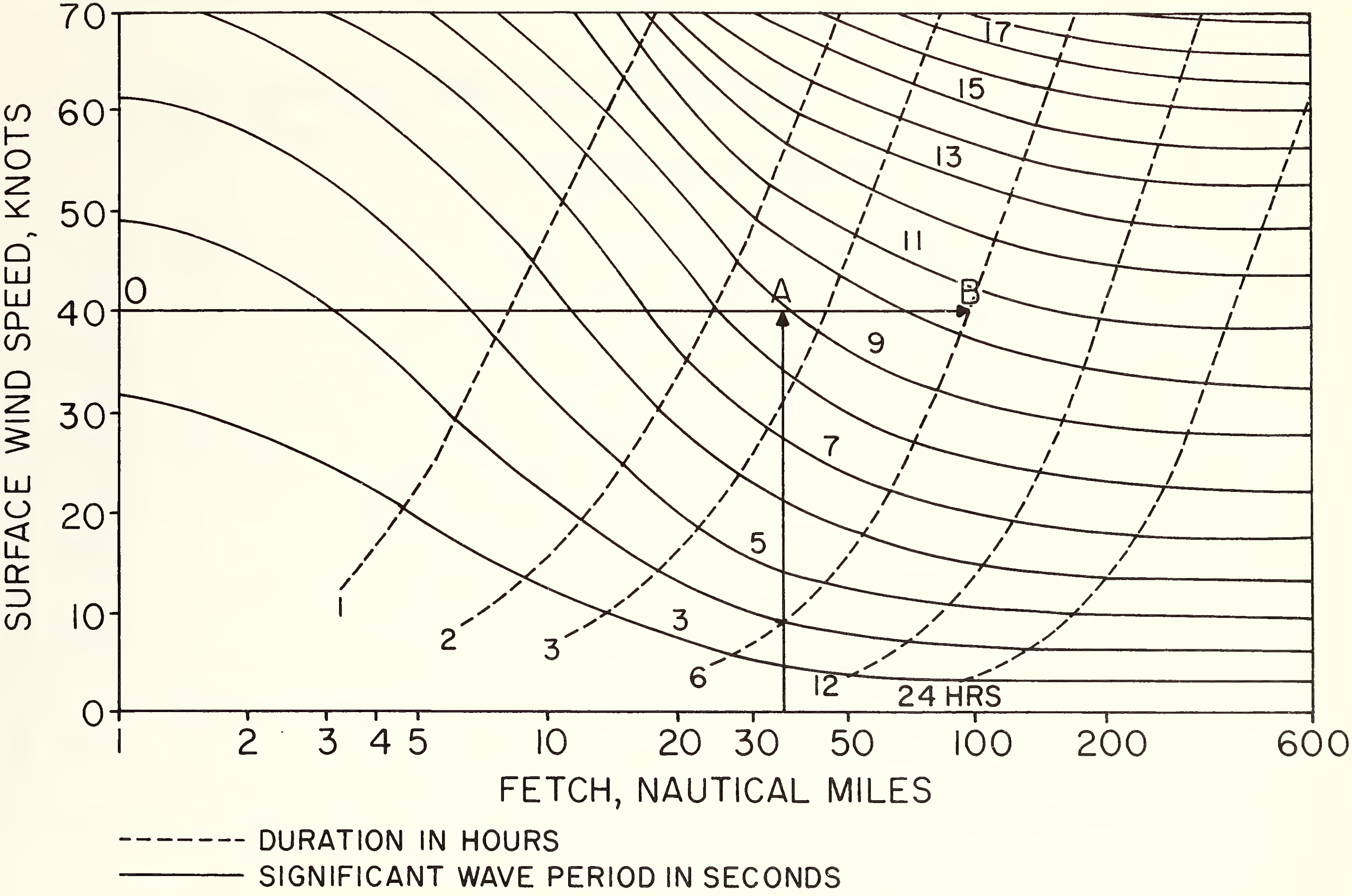

Figure 22 - Graph relating wind speed to wave period with constraints of duration and fetch -oceanic waters.

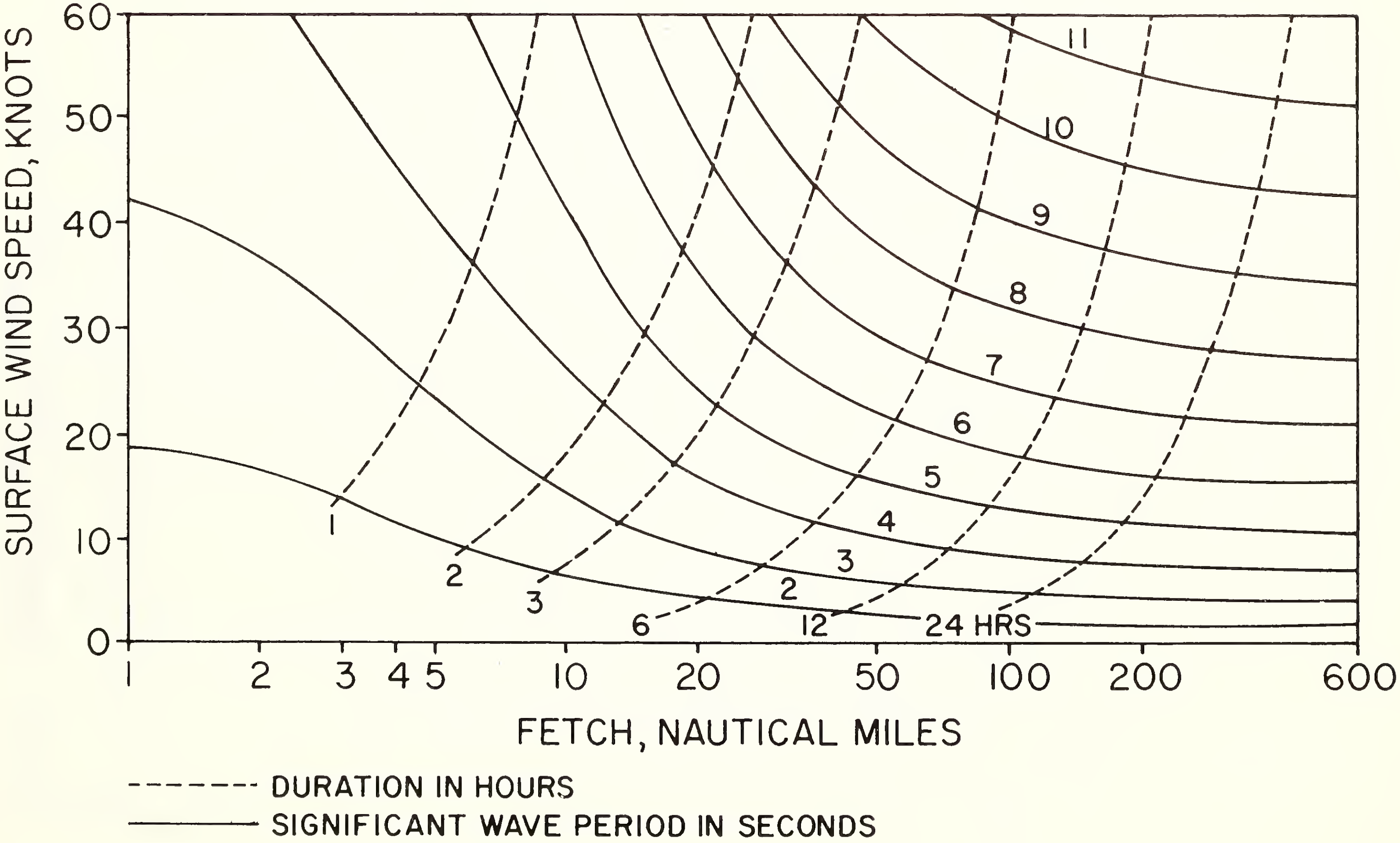

Figure 23 - Graph relating wind speed to wave period with constraints of duration and fetch -coastal waters (depth 100-150 ft.).

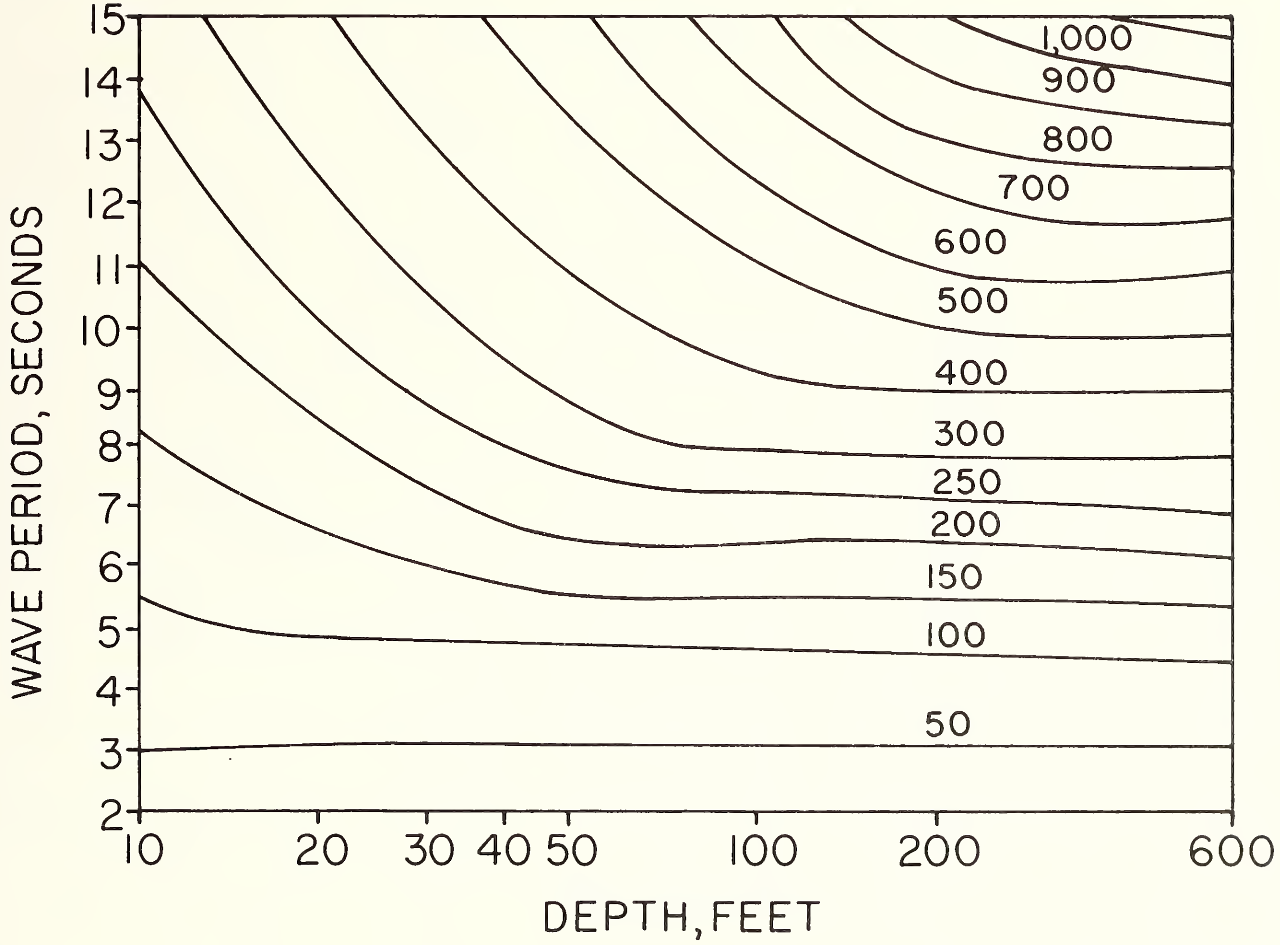

Figure 24 - Graph relating wave length to wave period and depth.

of water are known. A 10 sec. wave in 100 ft. of water has a wave length of 450 ft. It should be mentioned that as a wave approaches shoaler water and "feels" the bottom that its wave length decreases so that the period remains nearly the same as it was in deeper water.

Note: *The heights derived from Figures 20 and 21 are the maximum wave heights likely to be encountered.* The maximum wave height should be multiplied by 2/3 to give the significant wave height.

7.3 Diagrams taking into account air mass/sea surface temperature characteristics. Lumb, in 1963, developed a very simple graphical method for forecasting the maximum wave height in the central North Atlantic based on observations and measurements made by the Ocean Weather Stations INDIA (59°N 20°W) and JULIET (52.5°N 20°W). One of three straight line relationships is chosen, as follows:

I - For those occasions between September and April when cold air masses are flowing over warmer seas;
II - For those occasions between September and April when warm air masses are flowing over colder seas;
III - May to August when the sea is generally warmer than the air, and the lower atmosphere is generally stratiform in character.

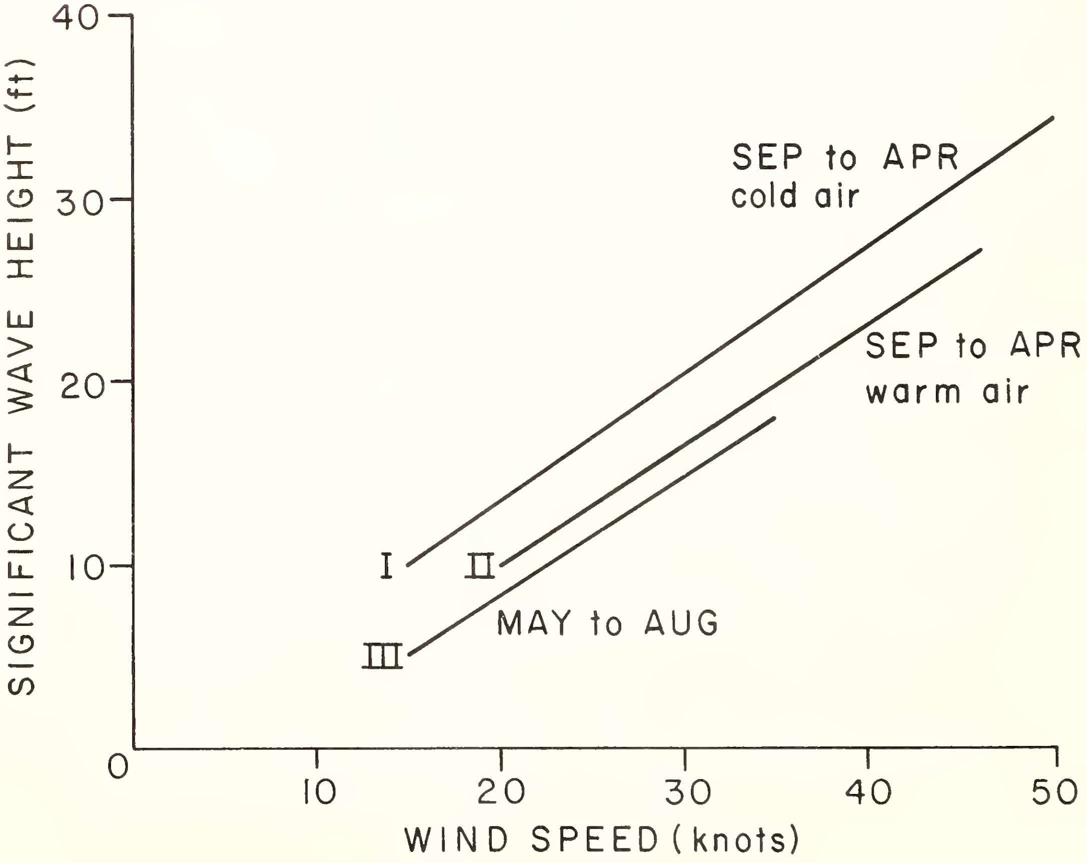

Figure 25 - Lumb's graphical method of forecasting maximum wave height in North Atlantic.

These graphs are reproduced in Figure 25, the ordinates being wind speed and maximum wave height. The wind speed used as the abscissa is the mean effective wind speed derived from ship reports in the locality or when there are few reports, from the geostrophic winds of prognostic charts with the appropriate corrections applied for curvature of the isobars. It takes time for the wind to raise a sea, and an allowance needs to be made for this lag when employing Lumb's graphs. Thus, suppose it is required to forecast the significant wave height twelve hours ahead. The wind value used should not be the forecast wind for that time. Some three to six hours of lag should be introduced in the computations (see Chapter 12) and a mean speed employed for the preceeding period. Thus, Lumb suggests use of the wind speed $V=\frac{1}{4}(V_1 + 2V_2 + V_3)$ where V_1, V_2, and V_3 are reports at consecutive six hourly intervals. Statistical evidence (see Chapter 12) suggests that a better result is obtained from wind values or forecast wind values made in a similar way with a three hour interval of time between. Thus, for forecasting the significant wave height twelve hours ahead, the figure to use for V might be $\frac{1}{4}(V_{+6} + 2V_{+9} + V_{+12})$.

Master mariners are of the opinion that if only the wind speed sequence can be forecast for them accurately for 24 hours or more in advance, their experience enables them to take evasive action from the worst effects of sea and swell, which they can judge with fairly high accuracy.

This view deserves greater attention, and since this type of diagram is attempting to incorporate (in a climatic as opposed to a synoptic sense) air mass/sea surface temperature differences, it is believed by the author to be of greater practical value to shipping than the complicated diagrams reproduced earlier in the chapter. With the correct use of perhaps one or two simple diagrams, the master of the ship can determine the expected growth rate of seas and take tactical action if necessary to avoid the worst of the weather in the next few hours ahead on his voyage. This subject is discussed in Chapter 12.

7.4 Modifications to Lumb's diagrams taking into account synoptic thermal structure of the atmosphere and the sea surface temperature gradient. Lumb used one of two graphs in the winter period from September to April according to whether the air temperature was warmer or colder than the sea surface temperature. It has been demonstrated in previous chapters that the degree of bite of the air mass on the sea surface necessary to raise seas depends on the stability of the atmosphere which in turn depends on how the air mass flows across the sea surface temperature gradients. In effect, Lumb's diagram is taking this into account. It is believed that on almost every occasion it is possible to categorize into one of five types according to the synoptic situation prevailing at the time. These types are essentially refinements of the classifications of air mass made in Chapter 5.

Type I defines an arctic continental air mass originating over an ice bound surface and subsequently flowing over a comparatively warm sea surface. Katabatic wind flows in winter often fall within this category. Generally $(T_{sea} - T_{air})$ is greater than 4 °C; a further more reliable factor is that $(T_{sea} - T_{dew\ point})$ is greater than 7 °C. The satellite cloud pictures typically show closely packed cloud streets, and the cloud type reported by ships at sea might be low cloud 9 (cumulonimbus).

Type II defines a polar maritime air mass modified by some length of sea passage flowing across a sea surface temperature gradient from the colder towards the warmer side. It typifies meridional flow over the oceans. The air mass is unstable and is characterized by a relatively low dew point. Cloud reports would be of low cloud type 8 (cumulus) with satellite pictures showing typical cellular type structures. In this case $(T_{sea} - T_{air})$ would be generally greater than 2 °C but less than 4 °C; $(T_{sea} - T_{dew\ point})$ greater than 3.5 °C but less than 6.5 °C. This type should seldom be determined from wind direction only since polar maritime air may have experienced recurvature.

Type III defines average circumstances with the air mass flowing approximately parallel to the sea surface isotherms; typical zonal flow in the west-east direction. $(T_{sea} - T_{air})$ will be small but positive, $(T_{sea} - T_{dew\ point})$ will lie between 0.5 °C and 2.5 °C. Satellite cloud pictures will not always be of great value since many cloud types may be present. Stratiform clouds in the upper atmosphere may conceal the cloud types near sea surface.

Type IV defines a tropical maritime air mass flowing across sea surface temperature gradients from the warmer towards the colder side. The lower atmosphere is generally stratiform in character and stable. The visibility is seldom better than moderate and is often poor. Fog or mist patches may be in evidence. Such circumstances are often encountered in the warm sector of a depression, but not exclusively so. The reported cloud types by ships will generally be stratiform low clouds 5, 6, or 7 (stratocumulus, stratus, fractostratus, fractocumulus).

Type V defines a warm, dry continental air mass flowing across a cold sea surface area which may have resulted from upwelling. In these cases the air mass is too dry to give rise to much fog or precipitation. (T_{sea} — T_{air}) and (T_{sea} — T_{dew}) will both be negative.

The five graphs connecting significant wave height and wind speed are shown plotted in Figure 26. It will be seen that the curve (dotted line) corresponding to the average circumstances (type III) agrees very closely with Figure 49 reproduced in Chapter 12. The air mass/sea temperature classifications used in Figure 26 are:

I - Arctic air mass flowing over warm sea.
II - Polar maritime or recurved polar maritime flowing over warmer sea.
III - Air mass flowing parallel to sea surface isotherms (average conditions).
IV - Tropical maritime air flowing over colder seas.
V - Warm, dry, continental air flowing over cold seas (upwelled water).

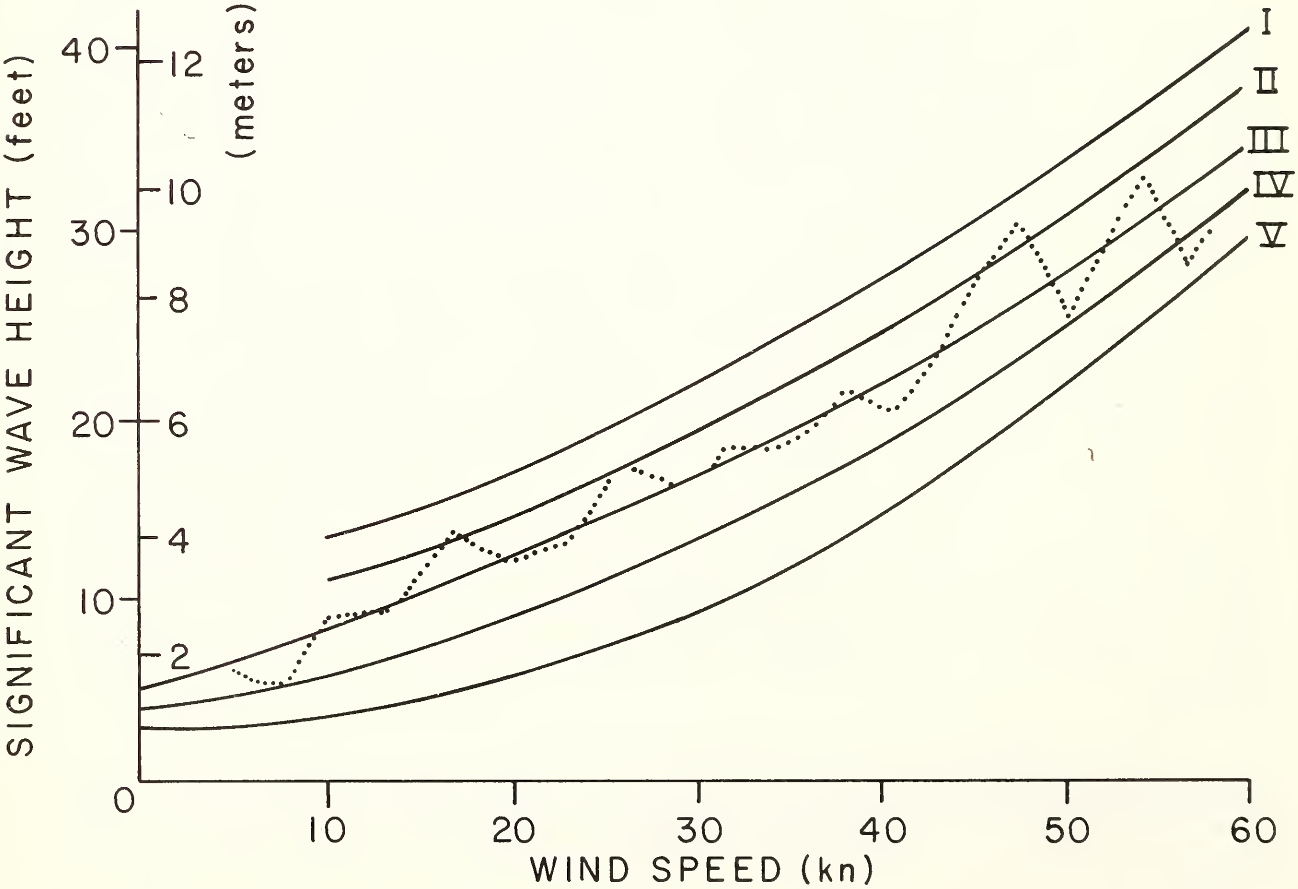

Figure 26 - Brittons's modification to Lumb's diagram.

7.5 Limitations of the technique. The method seeks mainly to forecast the sea conditions brought about by a developing wind situation, but it is believed that it provides a better answer to forecasting the steepness of waves in the early stages of development of a storm than other conventional diagrams. It takes no account of a swell from a distant storm. Obviously, when heavy swells are crossing the area from a distant source, they introduce an additional consideration. When a swell of known wave height enters an area where waves are being generated by local wind stress, the wave heights must be computed since they cannot be added linearly. The relationship is a complex one, but an approximation to the combined height can be derived from the formula:

$$H_{1/3} = \sqrt{h_1^2 + h_2^2}$$

where h_1 and h_2 are the significant wave heights of the wind waves and swell, respectively.

It is to be noted that the straight line relationships given by Lumb and the modifications suggested to them do not pass through the origin. They were derived from measured data, which included some combination of sea and swell. At low wind speeds, with almost negligible seas, some swell would be present with more residual swell in winter than in summer. Lumb's diagrams do not give any values below 15 knots.

A forecaster using either Figures 25 or 26 should give some consideration to the effect of cross-swells from distant storms. If necessary, he may need to modify the value obtained for the significant wave height; although it may be generally more important for him to consider whether a straight isobar situation is likely to develop or major cold or arctic fronts will cross the areas of consideration in the forecast period. The effect of temperature changes must also be introduced.

7.6 Forecasts of wave periods. Forecasting the wave period or the wave length is of equal importance to forecasting the wave height, since it is in doing so that some indication can be obtained of the wave steepness that is often of far greater importance than the height. Under certain meteorological circumstances, the height develops far more rapidly relatively than the period. Experiments have shown that the spectrum (see Chapter 11) of fetch-limited growing waves exhibits a sharp peak. As waves grow while they are traveling under an increasing fetch, the energy of the spectral maximum appreciably exceeds the energy level to which the waves of this frequency finally adjust. During further development the peak shifts towards lower frequencies of longer period.

It is a deficiency of all wave period forecasting techniques that they make no allowance for this. Diagrams giving the period, such as Figure 27, represent only average conditions with periods and wave lengths based largely on theoretical considerations.

A forecaster can often make some allowance for the change from lower to higher periods by consulting sequences of spectral buoy data (see Chapter 12). Otherwise he needs to consider the three principal causes and make an estimation accordingly:

(a) The acceleration of the wind, consequent on a tightening of the pressure gradient.
(b) The passage of any cold or arctic front leading to increased bite.
(c) The consequence of any adverse currents or tides.

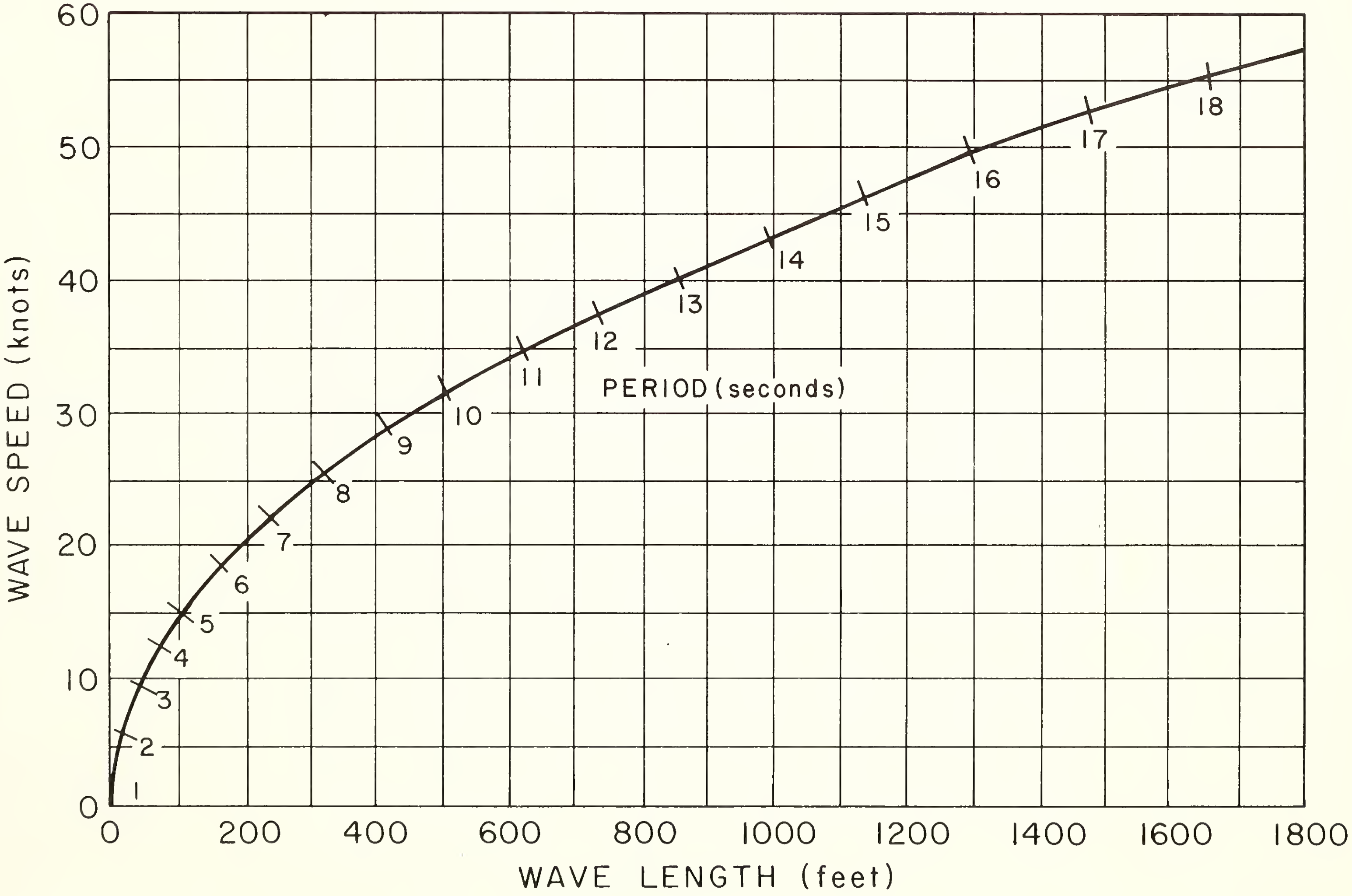

Figure 27 - Graph relating significant wave period to wave speed and wave length.

CHAPTER

8

THE DYNAMICS OF THE BOUNDARY LAYER IN THE OCEAN

8.1 Introduction. In Chapter 5, the problems of producing the best possible effective wind field chart was discussed. This is usually regarded as being the first essential, if not the only requirement, leading to a sea state forecast. But this can only be true for an ocean surface which has no characteristic or residual velocity due to extraneous causes. Generally, some elements of ocean currents, tides, or wind-driven currents are always present. A sea state forecast based only upon the dynamics of the atmosphere and which does not take any account of the dynamics of the sea will generally be inadequate and sometimes grossly in error.

Basically, wave formation results from the transfer of energy and momentum from the atmosphere to the sea, and it is insufficient to assume that the only inputs involved in the process come from the atmosphere in the generating area.

Some simple considerations will place the dynamics involved into better perspective. The density of water is about four orders of magnitude greater than that of air. Generally, current speeds are seldom more than one-half knot, although in some of the major current regions of the world, such as in the Gulf Stream, the Somaliland Current, and so on, or in tideways, water speeds in excess of five knots may be experienced. Average wind speeds at sea may be assumed to range between 15 and 20 knots, although in major storms or hurricanes, winds of 50 to 80 knots are experienced. From this it may be seen that air velocities lie between one and two orders of magnitude greater than water velocities. If we consider an ocean stratum to a depth of five meters and the overlying atmosphere to a height of 100 meters, it is easily seen that on average circumstances the momentum of the stratum of the ocean is at least one order of magnitude greater than the momentum of the overlying stratum of the atmosphere with the kinetic energies of the two having approximately equal value. In cases where the current or tides are exceptional, the momentum of the upper ocean is much greater than the momentum of the overlying air mass.

The speed with which waves are generated and their steepness in the formative stages is in large measure due to the impacting of the air mass on the sloping faces of the waves. By no means is all of the momentum of the sea surface layer created by the wind flow, and much depends on the momentum which was there initially and is maintained by currents, tides, inertial flow, and so forth. More damage to ships and cargo is caused by impacting water mass than by air mass impact.

The difficulty in sea state forecasting is to know or estimate such inertial water flow, which may be due to one of the following causes:

(1) Ocean current circulations.
(2) Wind-driven currents that may not necessarily be entirely local in origin.
(3) Tides.

In a large number of cases, such as in the open ocean, it may well be possible to neglect the current and tidal speeds when making a sea and swell forecast, but on continental shelves, in known areas of major currents, in tideways, and so on, the velocity possessed by the surface water could be the most important consideration of all for making a successful forecast.

8.2 Currents. Much information on the average flow of ocean currents of the world is charted in a good current atlas, and these are normally carried on board ships. It is not the purpose in this book to discuss in detail the general circulation of the oceans as seamen in particular will be well aware of how best to obtain such information for normal navigational procedures. Keep in mind that such current atlases only provide average values, usually computed on a monthly basis.

Currents behave like rivers in the sea -rivers which are not constrained by well defined banks or channels. They change course frequently. They meander and sometimes branch off to form eddies within the broad stream. Therefore, in dealing with the synoptic problem, it is just as unsatisfactory to use climatic ocean data as it is to use climatic weather data for a daily weather forecast. However, when synoptic data do not exist, it is generally better to use climatic data than to ignore the matter. Generally speaking, it is always necessary to take ocean currents into account when considering a forecast for an area lying within the main path of currents such as the Gulf Stream, the Agulhas Current, and so on, since there is a considerable degree of persistance.

The variations in the current paths are to some extent controlled by seabed topography, but surface winds can also affect the deviations from the mean flow paths. Essentially, what is required is to know the synoptic current flow. There are two main means of obtaining or assessing this information to the best obtainable degree:

(1) From sea surface temperature charts.
(2) From satellite imagery, particularly those which use enhancing techniques to show surface water discontinuities by infra-red measurements.

These methods will now be discussed in more detail.

8.3 Sea surface temperature charts. Sea surface temperature charts are prepared from the reports of sea surface temperature measurements by ships of opportunity. Occasionally, measurement made by aircraft carrying airborne radiation thermometers can be incorporated and greatly enhance the products. However, the number of shipping observations received on any one day is seldom sufficient to produce a meaningful daily sea surface temperature chart so it is usual to collect the values over a few consecutive days and construct a mean map. Many weather services produce a five-day mean map routinely every one or two days. The fewer the number of days necessary to make a mean chart, the greater the value of the product and the more it approaches the desirable synoptic state and is effective in indicating the areas affected by wind driven surface currents.

8.4 Measuring sea surface temperature. It is unfortunate that ships have no common method of measuring the sea surface temperature. The parameter which is of maximum value is the skin temperature of the water surface, for it is this parameter which is the one to use in assessing air mass stability, the evaporation rate, and the chances of sea fog formation or dissipation. The closest estimate to this value is obtained by taking the temperature of a bucket sample from a point as far forward as possible on the deck. It is a difficult operation requiring some skill and good measurements are only obtained with care. Such values should always be used for constructing sea surface temperature maps, but it is seldom possible to ensure that this is so. Ships having a high freeboard and steaming faster than 17 knots need a special type of bucket (the Crawford bucket), but even so, it is difficult to get the bucket into the water to obtain a sample of surface water. In such vessels it is usual to measure the temperature in the water intake to the engine room. The intake temperature never represents the true temperature of the sea surface, and it is a particularly inaccurate measurement when the upper layers are highly stratified.

If reference is made to Figure 4 in Chapter 3, it will be seen that a ship with a large draft and an intake point more than 5 meters below the surface would record a temperature over 2.0 °C lower than the true sea surface temperature. This is an exceptional case, but it highlights the problem. No distinction is made in ship synoptic reports between values of SST obtained by bucket or at an intake. In certain areas, particularly in the summer in stable conditions, a considerable range of temperature may result. Fog formation very critically depends on the values of ($e_W - e_a$). Values of ($e_W - e_a$) are derived from the sea surface temperature T_S and the dew point T_D. For good forecasting, it is desirable to measure sea surface dry and wet bulb temperatures to an accuracy of 0.1 °C. It is possible to do this, but it is difficult to do it well. A recent instrumental development in this field has been the production of a low cost towed thermistor which overcomes the difficulties of using a bucket. It has given good values when used in a hovercraft moving at more than 30 knots.

8.5 Some examples of sea surface temperature charts. Figure 28 represents a 10-day mean sea surface temperature chart for the North Atlantic, and Figure 29 is a mean monthly sea surface temperature chart for the Northeast Pacific that is based upon the shipping observations from a large number of years of data. It is seen that on the western side of the North Atlantic the isotherms are tightly packed.(A similar pattern also occurs in the western Pacific.) The 10-day mean chart reveals the meanderings of the ocean currents as they wend their way across the ocean forming elongated tongues of warm or cold water. Storms crossing the ocean complicate the patterns because they tend to drive the warm surface water so that it overrides the colder water patches.

8.6 Sea surface temperature charts from satellite measurements. The time may be approaching when SST charts will be obtained on a regular basis by satellite measurements from outer space. If this is so, some of the problems associated with the drawing of sea surface temperature maps should disappear, and they will become more acceptable to meteorologists as aids to forecasting in marine areas. Hopefully, they will provide an accurate synoptic map, much superior to the present 10-day mean charts based upon a mixture of bucket and intake temperatures. It is already possible to identify patterns in the ocean on the infra-red images using the enhancing techniques, and an example will be discussed in detail in Chapter 9.

The interpretation of these pictures needs further experience and research as the technique does not presently provide very accurate actual measurements of the sea surface temperature. The pictures probably indicate more clearly the location of the density discontinuities, which are convergence zones due to currents and thus provide a useful aid to sea state generation. If it becomes possible to provide actual temperature charts, it will constitute a major advance, since they will improve the accuracy of air mass/SST classification and enable better estimates to be made of air mass modifications due to passage over a sea surface. The patterns already available indicate a high degree of persistence and immediately show any onset of upwelling. This alone is of some importance in sea and swell forecasting in coastal waters.

8.7 Tides. Off entrances to ports, in estuaries, and continental shelves generally, tidal effects may be of greater importance in sea state considerations than current flow. Tidal currents in excess of five knots are not uncommon in estuaries and may be a serious hazard, particularly to yachts and small ships. It is not the intention to go into tidal theory in this book since many reference books are available which deal with the subject in detail. Only a brief outline will be provided here.

The attractions of the moon and the sun of the water covering the earth's surface are the cause of tides, the main influence being that of the moon because of its proximity to the earth. The values of the tide raising forces of moon and sun are approximately in the ratio of seven to three. Hence, there are two tide raising forces which act at an angle, and the composite effect will depend on the degree to which they assist or oppose one another. Both heavenly bodies act in such a way that they cause diurnal and semi-diurnal components of tide. The greatest effect occurs when they act in conjunction just after full or new moon; there being a lag of between one to two days. These tides are called spring tides. Just after the first or the third quarter, the tide raising forces act in opposition, and the tidal effects are minimal. These are known as neap tides.

Generally, there are two high and two low tides about every 24 hours and 50 minutes, but there are exceptions depending on whether the diurnal or semi-diurnal components predominate. The difference between the height at high water and the height at low water is called the range of the tide. The greatest ranges are to be expected, therefore, at springs and the smallest ranges at neaps. Correspondingly, the strongest tidal flows will be experienced halfway between low water and high water when the tide is on the flood and also halfway between high water and low water when the tide is on the ebb. For sea state generation, it is generally more important to

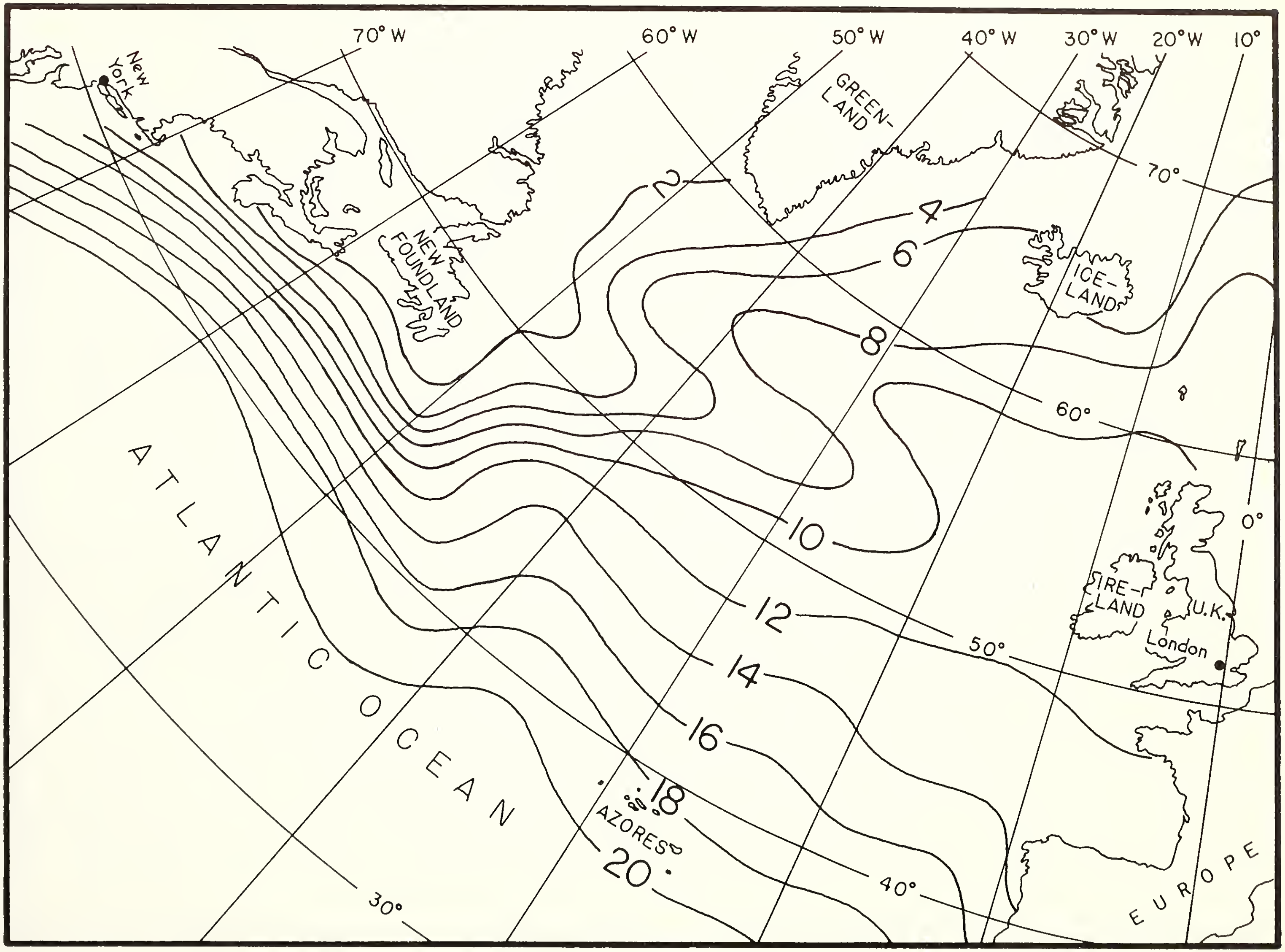

Figure 28 - Ten day mean SST chart 21-30 May 1972 (in °C).

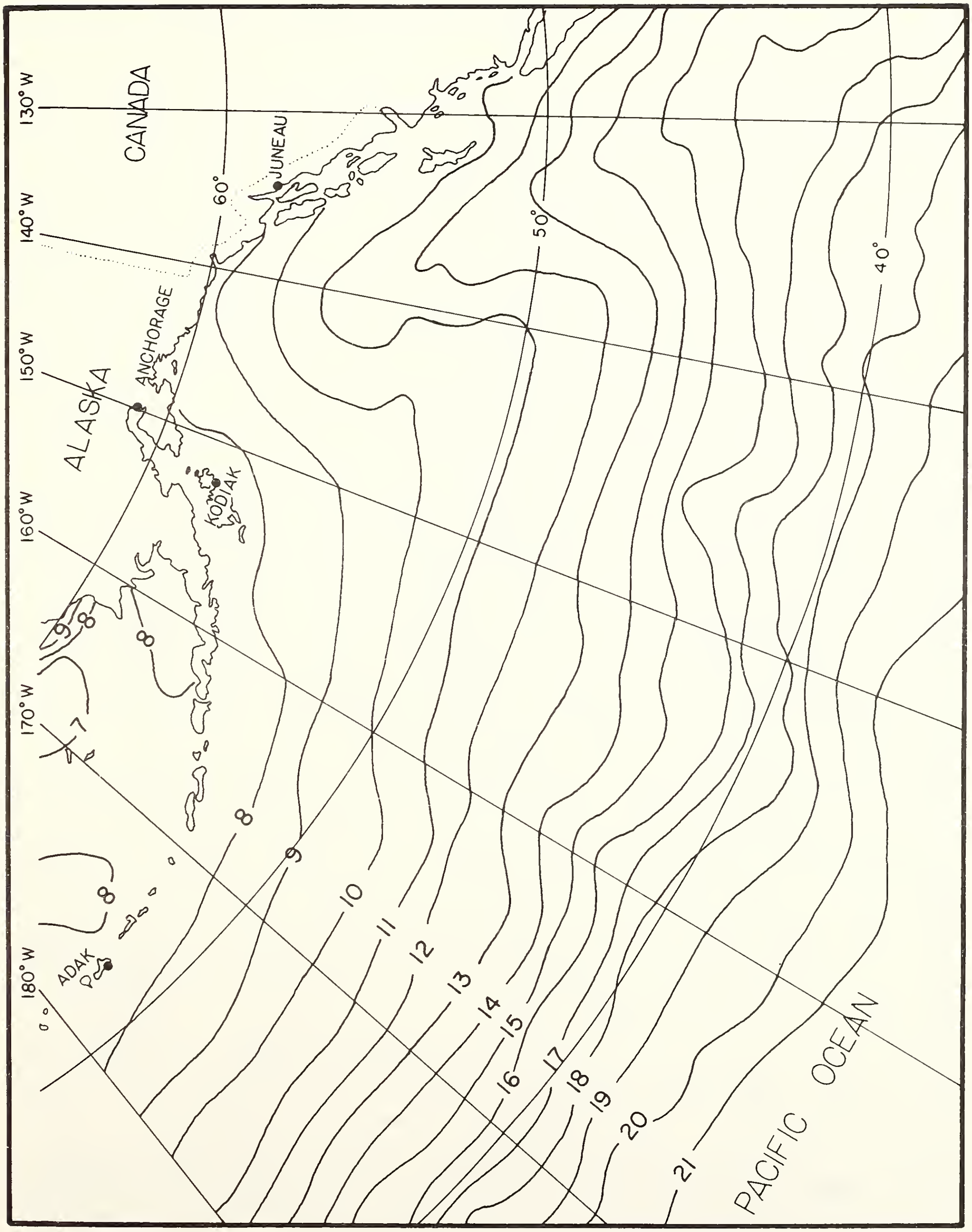

Figure 29 - Mean monthly SST chart for October (in °C).

consider the ebb tidal flow against the incoming swell.

Ranges vary considerably on the continental shelves and depend very much on the slopes of the bottom. The speed of tidal currents will likewise vary. Open ocean tides are seldom great and can be safely ignored in practical forecasting.

Estimates of tidal currents can be obtained from tidal current tables or atlases published by various government agencies. In the United States, the National Ocean Survey of NOAA annually publishes tidal current tables for areas along the Atlantic Coast of North American and the Pacific Coast of North America and Asia. Daily predictions of slack water, maximum flood, and maximum ebb currents are given for a selected number of reference stations. Supplemental locations are then referenced to these primary locations, and corrections to the times and velocities of currents at the primary stations are made to arrive at the currents at the secondary sites. For example, San Francisco Bay Entrance is one of the reference locations and has over 130 other locations referenced to it.

Additionally, a number of tidal current charts are also published for major waterways in the U.S. that show the current patterns in some detail. Generally, we will be interested in the maximum effect experienced at the ebb current since this is the one that usually flows against an incoming swell. It may be necessary, however, to consider the flood as well if the wind is blowing across a sufficient fetch of several miles in opposition to a current of about three knots or higher. Steep seas will be raised in these circumstances.

The stage of the tide, on the other hand, is determined from the tide tables, which are also published annually by the National Ocean Survey. These tables, unlike the ones for the currents, are for locations worldwide and consist of about 198 reference stations and about 6,000 secondary locations.

8.8 Wind-driven currents. Synoptic situations that result in the worst sea and swell conditions are often associated with the development of a large meridional wave in the atmosphere (called a Rossby wave) followed soon after by a prolonged period of strong zonal flow from west-southwest toward the east-northeast. Meteorologists should have no difficulty in recognizing why this should be so. A number of lows will generally have been associated with the mean zonal flow, and the strong westerly winds will have generated or assisted some flow of warm surface water in a northeasterly direction. Subsequently, with the development of the large scale Rosby wave a strong northerly outbreak of cold air occurs on the eastern flank of an anticyclone often with straight isobars or ones with slightly anticyclonic curvature. A number of cold fronts move in a generally southerly direction opposing the warm water flow northeastwards, which was generated by the zonal flow. Such conditions will favor the generation of waves of maximum steepness.

A useful computer product for use in a marine forecasting office is a chart derived by gridding consecutive sea surface temperature maps five days apart. Observations are not common to the two charts, and the product indicates surface water temperature changes and the areas of surface water advection. Figures 30 and 31 represent two charts obtained by gridding the mean sea surface temperature charts with those obtained five days later. A case has been chosen where storms crossed the areas, first from a westerly and then from a northerly direction. In the first gridding process, it is seen that in certain areas the SST rose by over 3 °C. This resulted from strong southwesterly winds occasioned by a deep depression which moved from west-southwest to east-northeast on 17-18 August with the center passing just to the south of Iceland. The second chart (five days later) shows areas off Norway where the SST has fallen by more than 4 °C. These falls followed a cold northerly air stream flow over the Norwegian Sea and the North Sea that quickly destroyed the superficial warm surface water as it extracted energy from the sea surface rapidly.

It is also advantageous to draw charts of the temperature difference between the sea surface temperature and the dew point of the atmosphere. The superimposition of the effective wind field chart onto such a map reveals immediately the areas of high evaporation rates and the direction of transfer of latent heat energy. These are the areas of high air-sea interaction, where the generation of sea and swell is a maximum.

The initial analysis of a sea surface temperature chart demands a high degree of manual skill and should always be drawn as carefully as possible by an experienced marine meteorologist, particularly in those areas of marked thermal gradients, such as the regions of the Gulf Stream or areas of ice melt in the spring. Equally important are those offshore areas which are subject to strong offshore wind flow. These areas in winter could result in large differences between the dew point of any cold dry air mass and the relatively warm sea. Such air

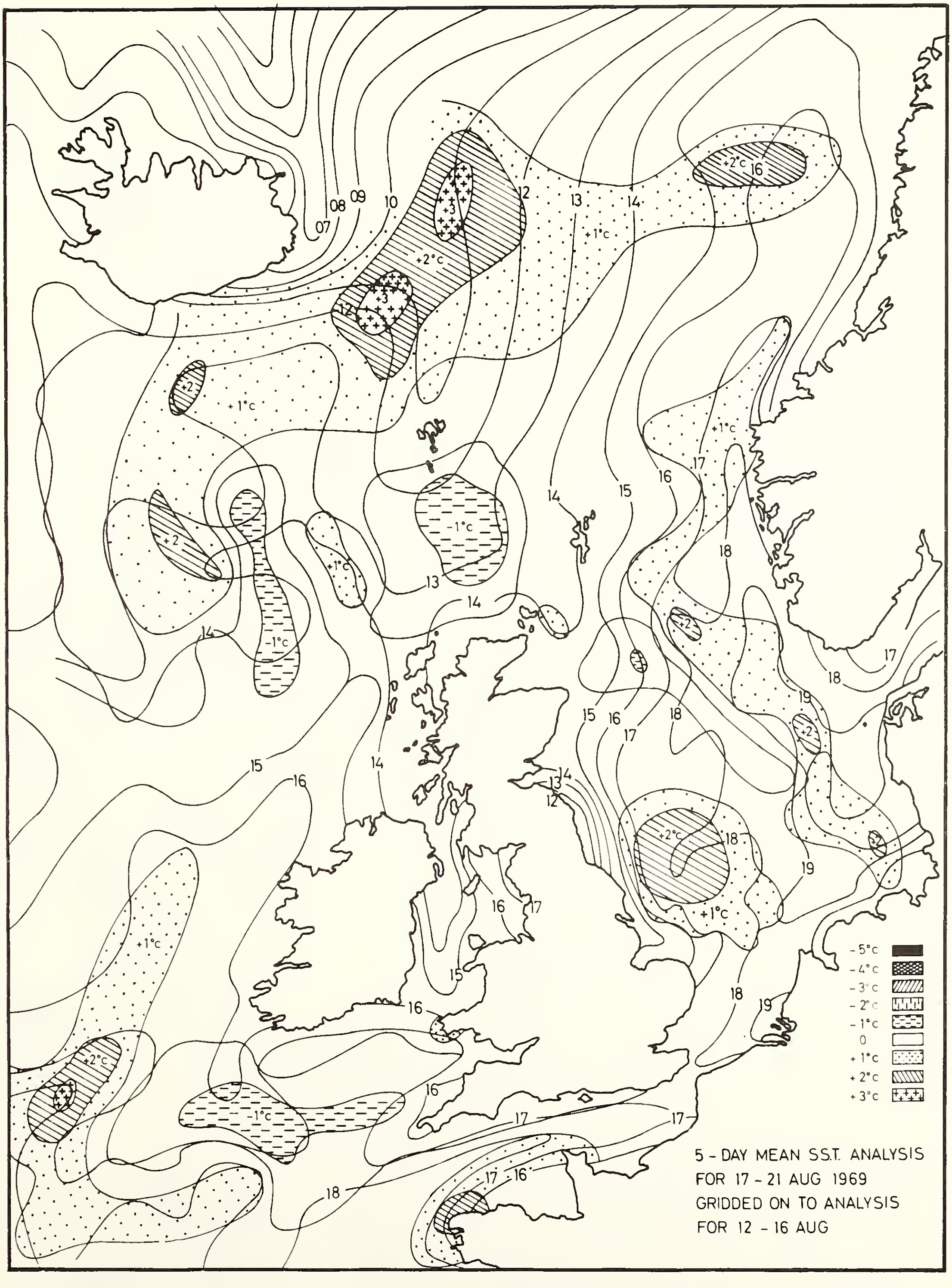

Figure 30 - Five-day mean SST analysis for 17-21 August 1969 gridded onto analysis for 12-16 August 1969.

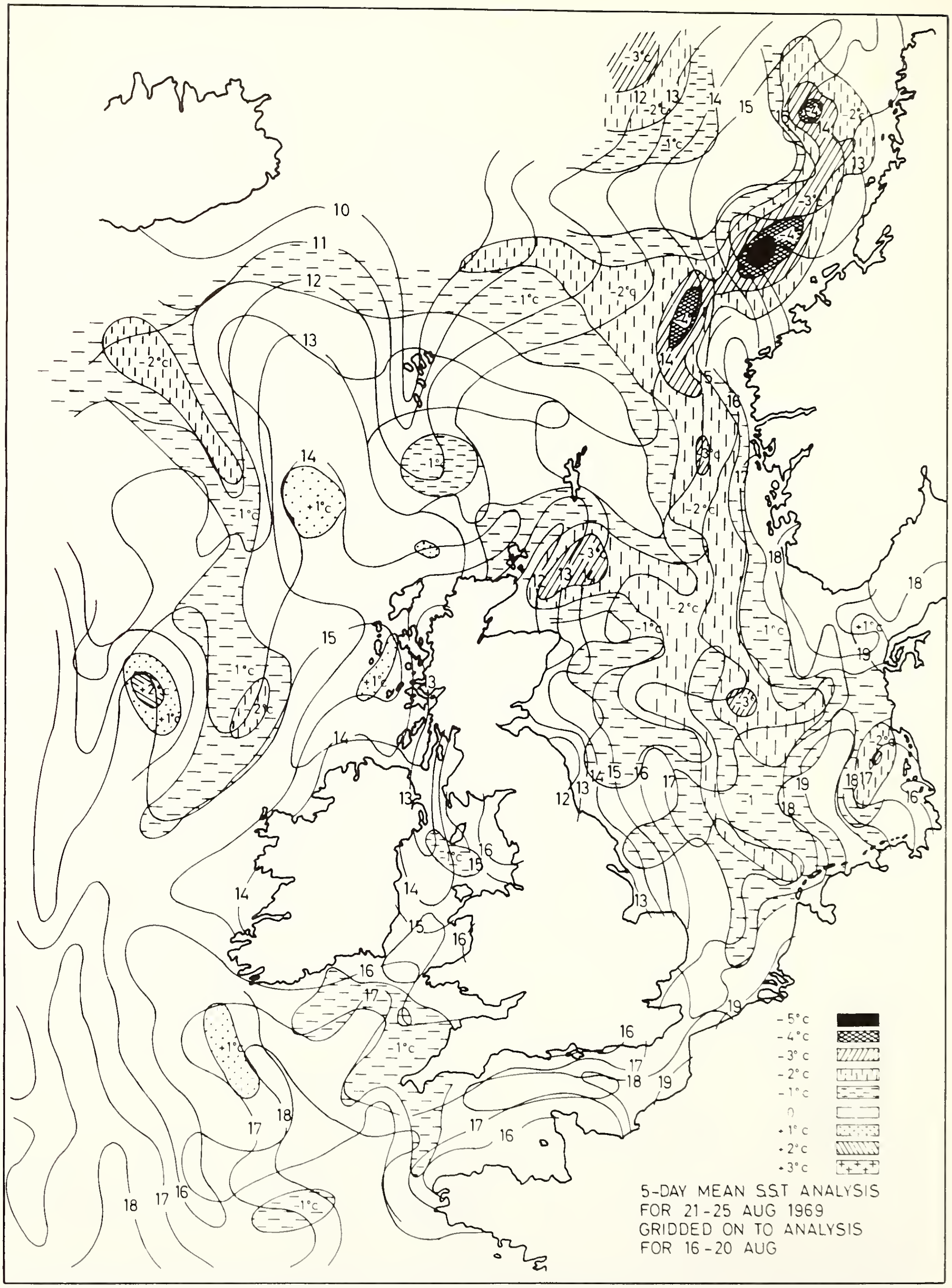

Figure 31 - Five-day mean SST analysis for 21-25 August 1969 gridded onto analysis for 16-20 August 1969.

masses are capable of raising steep and dangerous seas in a very short space of time. Consultation of satellite cloud imagery can aid such analyses. Over cold water, the skies are often cloud free, particularly over upwelled water to the west of land masses.

In areas of tight thermal gradients, currents are strong. Some attempt should always be made to identify oceanic fronts since there is usually a marked surface current discontinuity at any oceanic front. The surface of the water appears to be a different color on one side of the front because of the different attitudes of wind to water. Often the water is broken, and whitecaps are visible on one side, whereas whitecaps are absent or less obvious on the other. On the warmer water side, convection will occur in the atmosphere, and the vertical currents will cause increased turbulence. This affects the degree of bite which the air mass exercises on the surface. The different effects sometimes create an impression to the eye of a water discoloration.

8.9 Summary. Currents and tides have a profound effect on the steepness factor of waves, particularly when the wind is opposed to the water movement. Seas then tend to mushroom, making small ship handling difficult and sometimes highly dangerous if quantities of water are raised and crash on to the decks. There are no practical means readily available for ships to measure and report current flow, but a forecaster can make some allowance by possessing a knowledge of currents and tidal effects in coastal waters, and he should always endeavor to take these into consideration when forecasting waves.

In inland waters between islands, some knowledge of tidal flows is desirable, such as in estuaries where the range of tide is considerable. Small boat fishermen and yachtsmen who use the waters affected by tidal rips know only too well the difference in behavior of the waves when the wind blows with or against the tide. Very few meteorologists are trained to use tide tables or appreciate the difference tidal currents can have on sea and swell behavior at spring tides. In certain cases, sea and swell forecasts may be required at a particular location that is making weather observations routinely (*e.g.,* at an ocean station ship or an oil-rig platform). If time permits, it is advantageous to maintain a continuous vector diagram of the wind speed from which to assess the possible effects of wind-driven currents.

CHAPTER

9

OCEAN THERMAL FORECASTING

9.1 Introduction. Most fish, if not all, are temperature sensitive to some degree, and it follows that a knowledge of the temperature distribution both laterally and vertically could be of value to the fishing community. But it should be understood that a number of factors are involved in the movements of fish schools, and temperature is only one of them and perhaps a minor one. Nevertheless, knowledge of the thermal structure of the upper levels of the ocean is always helpful for sonar performance, and the latter is an acknowledged operational aid to fishermen in certain ocean areas of the world. Hence, thermal structure of the upper layers of the ocean is an important subject that demands the attention of marine meteorologists.

Concentrations of fish are likely to be more heavily dependent on the distribution of their sources of food than on the temperature distribution, and it is during the summer months that thermal heating sets up thermoclines and convergence zones in the upper layers that restrict and concentrate the movements of small fish, which form the food chain for larger species. Across any density discontinuity, and many of them are sharp in the oceans, there is necessarily a velocity change. A convergence zone results, which entrains vegetable matter and small fish into the discontinuities.

A steady flow of offshore winds from the continents in summer leads to some degree of upwelling that brings water with fish nutrients to the surface. Upwelling results in the lateral formation of oceanic fronts. Information on the extent of the upwelling area is of value to fishermen and can be partially determined from sea surface temperature reports from ships aided on occasion by enhanced satellite images. However, a good sea surface temperature map by itself can never adequately answer the important question, "Where are the fish?" Some fish, such as tuna, are particularly sensitive to temperature and choose their habitat within waters having a narrow temperature range. But most are not, and therefore, temperature analyses are of little consequence unless they define where sharp thermal discontinuities exist laterally. Many orders of marine life are light sensitive, rising towards the surface with the aid of swim bladders in the evening and returning to the depths by day. This source of food for larger fish is restricted by and entrained into the thermoclines; thus, some species of fish are often to be caught if nets can be positioned correctly with respect to them. Cloud cover and the phases of the moon are factors which will sometimes influence a catch since these are factors which influence the light-sensitive fish.

Sea surface temperature maps cannot be expected to indicate the strength or depth of the vertical discontinuites across the seasonal thermocline. Vertical discontinuities are generally stronger than the horizontal distribution across oceanic fronts, although the temperature gradients in an oceanic front can be large if a considerable degree of upwelling has taken place.

Hence, it should be appreciated that information from a sea surface temperature map or a satellite image alone is somewhat limited causing it to be misleading in certain cases. To obtain the thermal structure sufficiently, some vertical soundings are desirable, particularly to identify the principal sheet levels, (*i.e.,* the depth of the density discontinuities between layers). Observations from expendable bathythermographs are sometimes helpful, although the instruments are not ideally suited to this task since they do not provide sufficient detail of the mixed layer to a depth of 50 meters. Often the best assessment of the mixed layer structure can be obtained with a good echo sounder, an instrument with which all fishing vessels should be equipped.

The layered structure in the top 50 meters is heavily dependent on weather changes, and it can be forecast to some degree by heat budget techniques.

Plate 3 is a reproduction of an echo sounder trace taken in the Strait of Gibraltar. The two dark bands on the trace show concentrations of small fish or plankton on the upper levels of the ocean. The darker band is the main seasonal thermocline at a depth of approximately 30 meters, but there is a transient thermocline with a lesser concentration of plankton at about eight meters. The wave form on the lines of plankton are internal waves caused by the tide flooding towards the Strait and breaking over a marked sill situated some 40 miles to the west of Gibraltar itself.

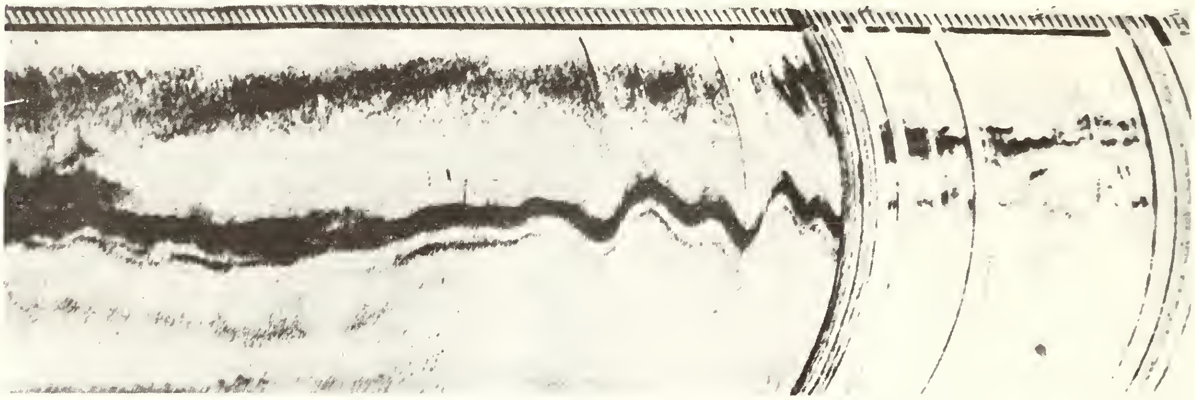

Plate 3 - Echo sounder trace taken in the Strait of Gibraltar.

It is of further interest to note that such internal waves impinging on the subsurface breakwater can extend right to the ocean surface. Plate 4 is a photograph of the radar scope at about the same time. The parallel lines represent the return echoes from patches of broken water on the surface, brought about in those areas where the internal wave crests break surface. The coastline of the Straits and several ships are readily identifiable.

9.2 The use of satellite imagery. Satellite images promise to be valuable aids for resolving ocean thermal structure, but their interpretation needs considerable expertise. The infra-red pictures give some indication of the temperature of the cloud tops -the degree of whiteness being inversely related to the actual temperatures. The same holds true of the ocean surface, and certainly the white areas in Plates 5 and 6 taken off the California coast are mainly areas of upwelled water, confirmed by low sea surface temperatures measured by coastal shipping. The vortices and whirls, which are features over the ocean away from the coast, are probably gyres resulting from density discontinuities, perhaps due to temperature differences, although they could result from other causes. The satellite sensors are measuring long wave back radiation, which varies not only with temperature but also with the character of the radiating surface. Color changes in water masses are unlikely to be revealed in the tones of the picture since the wave length band is well outside the visual band, but the roughness of the sea areas near oceanic fronts could well have some effect.

Across the sea surface boundary there is a temperature discontinuity of the order of 1 °F at all times.

Ed. note: Another location where internal waves break through to the sea surface is in the Sulu Sea between Borneo and Mindanao Island in the Philippines. (These waves have been detected by meteorological satellites.) Due to the interaction of tides with the underwater topography, internal waves are created in the thermocline layer of the ocean and often make their presence known at the surface as a series of 4 to 10 foot-high breaking waves that travel across the Sulu Sea in wavefronts that may be up to 150 miles wide. Naturally, the appearance of such waves to seamen can be quite frightening, for they suddenly materialize "out of nowhere", stretching from horizon to horizon on an otherwise calm sea.

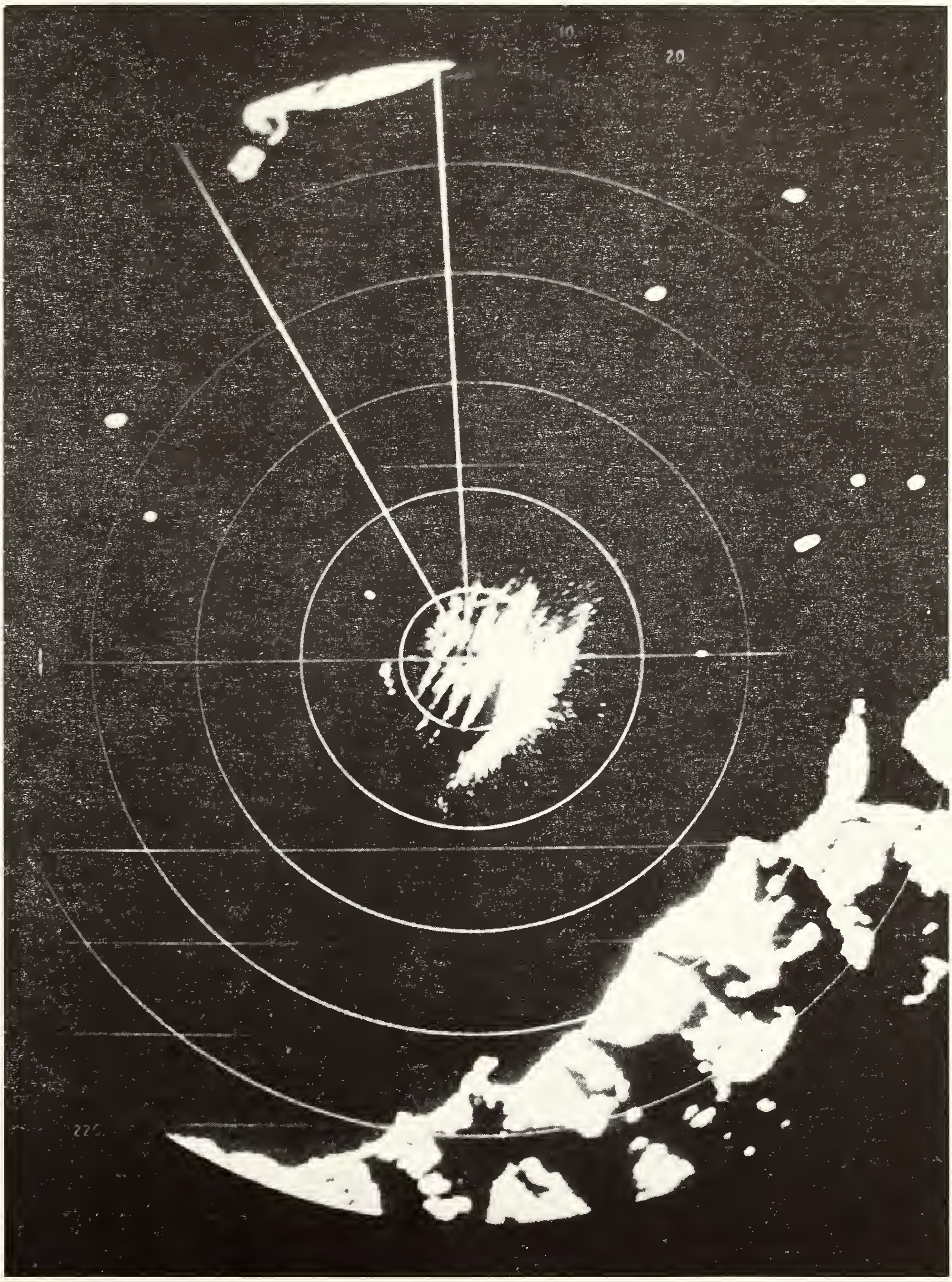

Plate 4 - Ship's radar scope showing the Strait of Gibraltar with internal waves created by incoming tide breaking the sea surface.

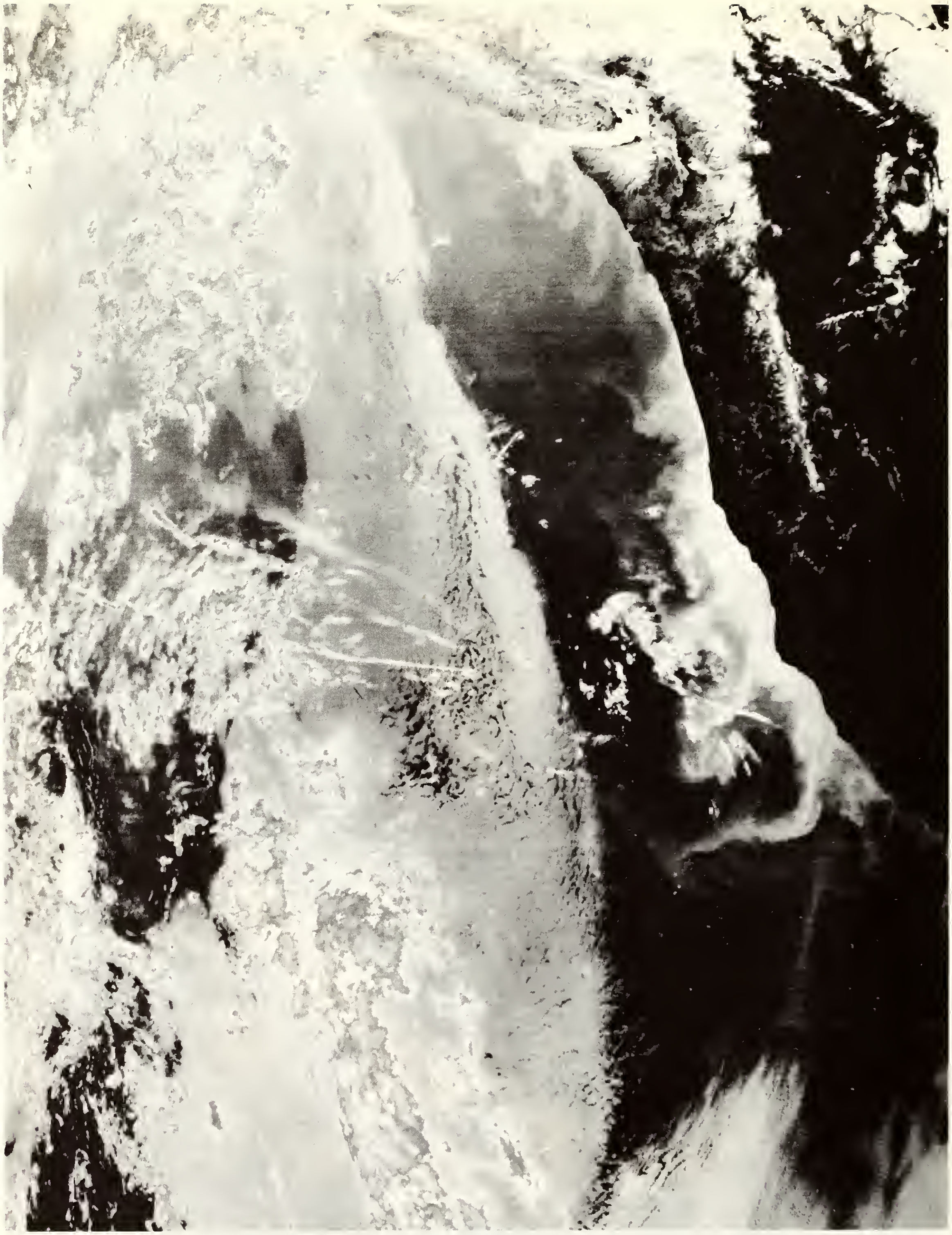

Plate 5 - Satellite picture of the Pacific Northwest Coast showing upwelling areas and aircraft contrails.

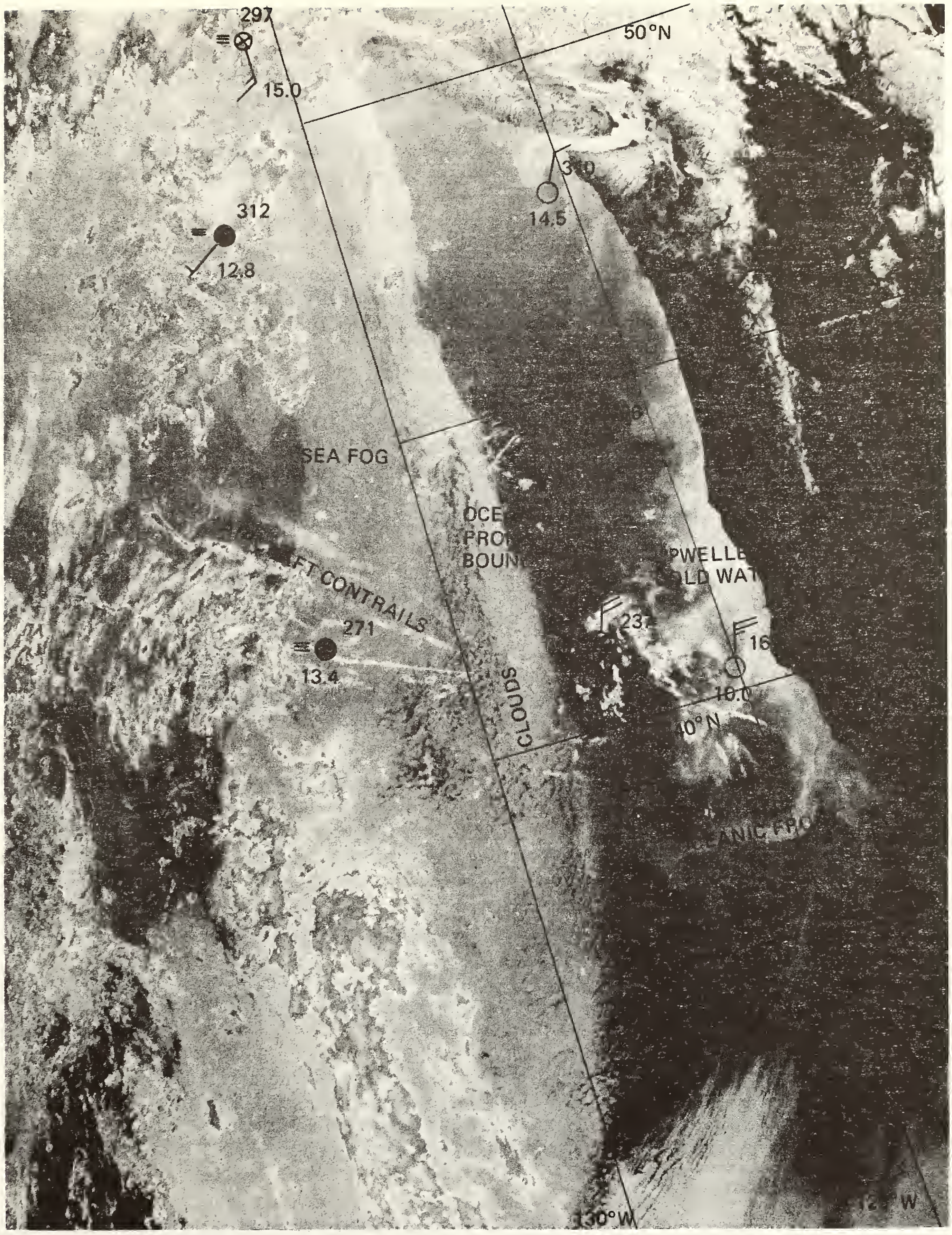

Plate 6 - Satellite picture of the Pacific Northwest Coast showing upwelling areas and aircraft contrails with grid and data superimposed.

Whenever the sea surface is ruptured and foam or white horses appear, parcels of energy are released to the atmosphere, white foam areas acting as windows through which heat escapes. Hence, we have the apparent anomaly that infra-red images of very broken sea surfaces might appear to be darker than calm seas. However, this effect would be offset by the increased amounts of spray, which would form a layer of particles, the upper level of which would be a cold surface. If there are particles in the atmosphere, such as created by smoke, the size of the particles is equally important, particularly if they act as nuclei for forming water droplets. The humidity content of the lower atmosphere is also involved.

Nevertheless, whatever the cause of the change in the color tones on the satellite picture, they would usually indicate density discontinuities in the upper ocean where concentrations of flotsam, plankton, and so on are forming. Hence, it is strongly justified to assume that the marked patterns in the ocean observed in Plates 5 and 6 do indeed represent some form of convergence zones, although not necessarily created by temperature alone.

It is also possible that they indicate some subsurface features since the sensing technique could have some degree of penetration into clear waters under calm conditions. Examination of the surface synoptic chart and in particular of the ship reports for that day, largely confirm the views expressed above. A few actual ship reports giving the wind direction, pressure, weather, and sea surface temperature have been plotted in Plate 6 on which a latitude-longitude grid has been superimposed to aid interpretation. A large anticyclone covered the area, and ships at approximately 300 miles from the coast were reporting widespread sea fog, clearly delineated as the white area on the satellite picture. The temperature at the top of a thick sea fog bank is colder than the sea surface owing to the radiation losses.

The straight lines which are a feature of the picture are probably aircraft contrails; although similar features are occasionally created by the funnel gasses from ships. These contrail-type phenomena often produce two sets of almost parallel lines with a distinct angle of cut between them. This results from aircraft or ships proceeding in opposite directions along a major route. Further research using enhancement techniques is necessary for the correct interpretation of satellite pictures of the sea surface. Actual temperature estimates from them must be used with caution for the time being

Obviously, satellite images have considerable value in delineating areas of sea fog, and this is of particular operational importance to fishermen in the Northeast Pacific where there is probably a higher degree of fog incidence in spring and summer than in any other ocean area in the world.

9.3 Thermoclines. The temperature discontinuities in the vertical are called thermoclines, formed as a result of the heating of the water by the input of energy from the sun. A typical summer distribution of thermoclines is shown in Figure 32. The top transient, which is at a depth of only five meters, forms on a warm afternoon and is called "afternoon effect." This is so named because of a marked deterioration in the performance of hull-mounted sonars on a hot summer afternoon caused by the refraction of the sonar beams in the surface layer. The main seasonal thermocline occurs over a band between 28 and 35 meters. Stirring action by the wind tends at all times to mix the uppermost layers and erode the transient thermoclines such as the "afternoon effect" to render the upper layers isothermal, or nearly so.

The degree of vertical mixing will depend on the strength of the wind and its persistence. Stirring action will not occur below 25 meters to affect the main seasonal thermocline unless a gale persists for some days. The transient thermoclines, which mainly form on calm days, are driven down by a later increase in the wind strength and gradually strengthen the gradients of temperature to form concentrations of discontinuities varying in depth between 30 and 40 meters below the surface. The difference in temperature between these two depths may be 10 °C or more. The concentration of gradients is referred to as the seasonal thermocline, but it does not represent one single discontinuity so much as a succession of discontinuities over one or two meters. The region above the seasonal thermocline and right up to the surface is called the mixed layer, and this layer is usually approximately isothermal, although it may well contain one or more transient thermoclines. The temperature discontinuity across an individual transient thermocline or sheet may be of the order of 0.5 °C to 1.0 °C. All the sheets are potential areas for concentrations of plankton and small fish, which are sources of food for larger fish.

The average depth of the seasonal thermocline is called the layer depth, and a knowledge of this depth would

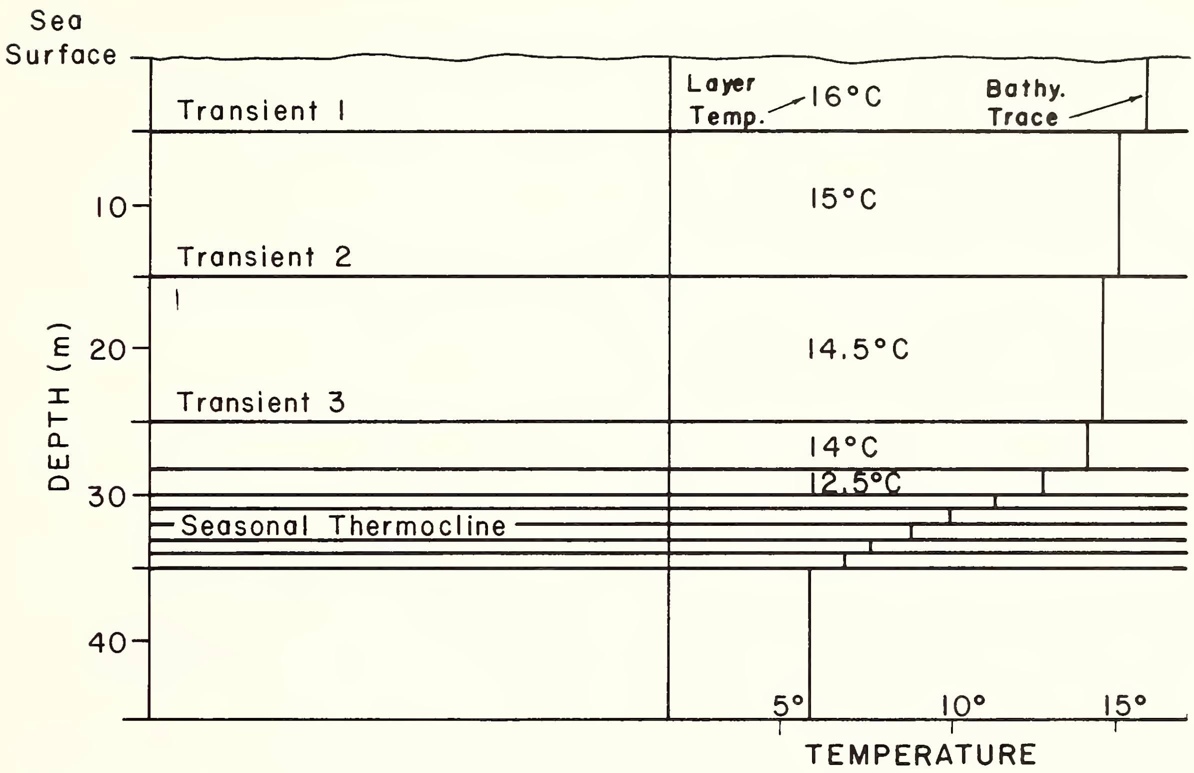

Figure 32 - Thermoclines.

be useful to fishermen, not only for fish concentrations, but also for sonar performance. This information can be obtained with a bathythermograph or a simple thermister probe, and the variations in depth can be forecast by taking into account the weather changes over the surface of the sea. This is done by a technique of heat budgeting, but it can be undertaken by programming inputs of standard weather data from ships in the usual WMO code forms.

Bathythermographs transit the mixed layer and the seasonal thermocline at some speed, and the response time of the instrument is seldom sufficiently fast to provide the detailed structure such as described above. A typical type of trace obtained from a bathythermograph is shown in Figure 33. One transient is shown at a depth of 10 meters with the main thermocline lying once more between 28 and 35 meters.

9.4 Heat budgets for the ocean. Although a sea surface temperature map, carefully drawn to observations and supplemented by comparisons with satellite imagery of the ocean surface, can provide a good indication of the horizontal temperature discontinuities and the location of oceanic fronts at the surface, it cannot be expected to convey detail of the vertical variations of temperature and salinity with depth and in particular indicate the layer depth.

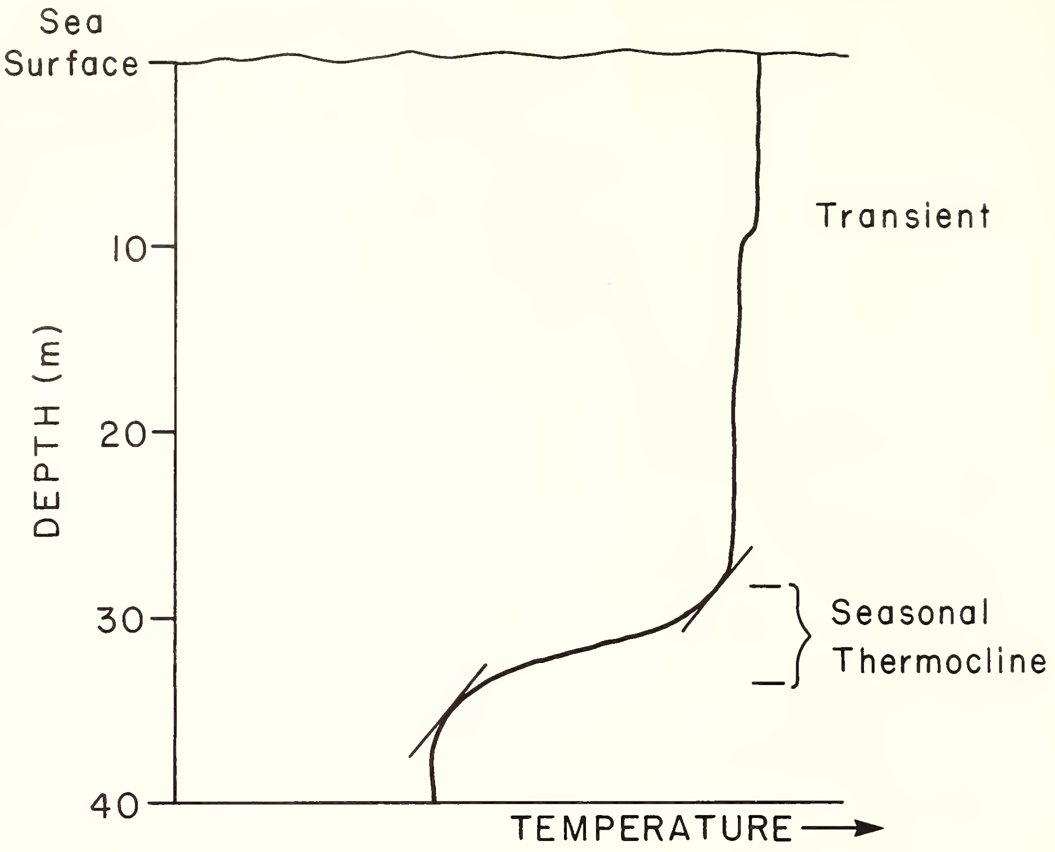

Figure 33 - Bathythermograph trace.

However, some idea of the depth of the seasonal thermocline in any particular area can be estimated from a sea surface temperature map, in combination with a few bathythermograph observations, particularly if the ocean surface is monitored simultaneously by a heat budget.

It is not intended in this chapter to go into any great detail on the requirements for heat budgeting, but certain observations will be made on the important factors involved. Further progress in satellite picture interpretation and improved empirical formulas for evaporation and back radiation could lead to simplifications in heat budgeting techniques to enhance their practical application.

9.5 Incoming solar radiation. It is sufficient to say that the total incoming solar radiation at the top of the world's atmosphere over any point on the earth's surface is simply a function of latitude, longitude, date, and time of day. Whether or not such impinging radiation is a variable quantity is a controversial question engaging the attention of many of the world's meteorologists at this time. It could well vary on a day by day basis as a result of sunspot activity, but for the present purposes it will be assumed constant and readily determinable from tables.

The amount of solar radiation which penetrates the earth's atmosphere to finally impinge on the sea surface then depends on the elevation of the sun and the amount and type of cloud cover. The latter effects can be estimated by empirical formulas, which have been deduced as a result of solarimeter measurements made on weather ships over a number of years in the North Atlantic. From such details, which can be found in many meteorological textbooks and papers, it is not a difficult matter to assess the amount of heat gained per unit area at any one spot on the ocean surface on any one particular day.

The classification of cloud types and amounts for use in heat budgeting differs somewhat from those internationally agreed on for describing and reporting cloud types and heights. This is unfortunate, but it is possible to reconcile the two sufficiently to enable a computation of incoming solar radiation to be made from a ship's report in standard code form.

It seems highly probable that an even more satisfactory estimate of solar inputs to the sea surface should soon be possible from infra-red, normal, and enhanced satellite images of the sea surface. At the moment, actual values of temperature cannot be deduced from these images, but comparisons with carefully drawn sea surface temperature maps should provide the required ground truths and improve the accuracy of estimations. Even without ground truth observations, an estimate of the sea surface temperature can be made if corrections are made for radiation absorption by atmospheric water vapor.

9.6 Back radiation. It may generally be assumed that the earth's surface, and the sea surface in particular, behave like a black body when radiating heat back into outer space. This occurs at all times of the day and night. The amount which actually escapes into space will depend once again on cloud type and amount; although the shielding effects of the clouds will not be the same as for incoming radiation since we are dealing mainly with long wave as opposed to short wave radiation. Empirical formulas have been developed for back radiation and generally contain the term T^4, where T is the absolute temperature of the ocean surface.

Loss by back radiation is relatively a much more constant flux of energy than the incoming solar radiation, which obviously varies greatly from season to season and with the time of day. It is generally of at least one order of magnitude less over the sea except in winter at very high latitudes.

9.7 Evaporation loss. The loss of heat by the ocean to the atmosphere by evaporation is the most variable term in the heat budget equation, depending heavily on the meteorological circumstances. In foggy weather with the overlying layer fully saturated, the loss is virtually zero, and there may even be some gain of heat by the ocean surface if there is some depositing of moisture from the atmosphere in the form of rain, drizzle, fog droplets and so on. In the contrary circumstances, when a strong wind is blowing that has a low relative humidity and is much colder than the surface temperature of the sea, evaporation is very rapid, and the moisture is quickly transported vertically by turbulent motions. It is also of note that it is in these circumstances that the wind can get a good bite on the ocean surface to raise a sea quickly.

Various empirical formulas have been developed for estimating the rate of heat loss by evaporation, and they can be said to be covered generally by formulas of the Dalton type:

$$E = (a + bU)(ce_W - e_a) \qquad \text{- - - - (9.1)}$$

where U = wind speed,
e_W = saturation value of the vapor pressure corresponding to the sea surface temperature,
e_a = vapor pressure of the atmosphere, usually measured at the height of 10 meters,
a,b,c are constants of which c approximates to 1. A value of 0.98 is frequently adopted over salt water.

Formulas of this type have proved to hold very well in winds of up to gale force (30 — 35 knots). At higher wind speeds, large amounts of spray are frequently torn from the crests of the waves in the turbulent air flow over the deformed surface, and an increase of evaporation may result from the spray itself. All seamen have experienced the sting in the wind when spray lashes the deck. This is due to almost solid salt particles hitting the face-spray from which the water has evaporated. Such circumstances only occur on less than 5% of occasions; hence, a correction for the increase in evaporation is a relatively trivial matter. Nevertheless, some suggestions are made in paragraph 9.11 for accounting for the effects of spray.

9.8 Sensible heat transfer. A transfer of some heat energy will tend to take place from ocean to atmosphere (or vice versa) according to whether the sea surface is warmer or colder than the overlying atmosphere. This process is partly due to turbulent transfer and partly to conduction, but is of a lower order of magnitude than such factors as incoming solar radiation gain or evaporation loss, except in rare cases.

9.9 Advection terms. A term that is frequently omitted from the heat budget equation is the advection term, but in certain areas of the world, it can be one of the most important ones. The major ocean currents such as the Gulf Stream, transfer vast quantities of energy continuously from lower to higher latitudes. One weakness of the heat budget technique is to make the assumption that the Gulf Stream does so at a constant rate. The Gulf Stream, as with other major ocean current systems, is subject to considerable variations of speed and track. This influences the transfer process considerably and has a big impact on the climate of the coastal zones adjacent to the current.

In addition, as was demonstrated in the previous chapter, storms are responsible for transporting warm water patches over considerable distances at appreciable speeds. The advection term in the heat budget equation is the most difficult of all to estimate; empirical formulas do not exist which enable an assessment to be made. Some allowances may be deduced from a consideration of the general wind pattern flow over the area of consideration during the previous ten days to one month. It is sufficient to compare such values with the prevailing monthly wind vector.

9.10 Heat budget equation. The heat budget equation may be formulated as follows:

$$Q = Q_I - Q_B - Q_E \pm Q_S \pm Q_A$$

where Q_I = effective heat input from solar radiation taking full account of cloud type and cover. It can vary in any one day from almost zero calories per square centimeter per hour to 150 calories per square centimeter per hour in low latitudes on a clear day around about noontime. Inputs for a day, therefore, in temperature latitudes might range from 50 to over 600 calories per square centimeter.

Q_B = effective back radiation into space taking full account of cloud type and amount. It is much more constant than Q_I and is occurring continuously. It accounts for a loss of about one order of magnitude less than the incoming solar radiation.

Q_E = loss by evaporation. This is a quite variable quantity ranging from zero calories per square centimeter to 40 calories per square centimeter per hour when a very cold dry air mass is flowing over comparatively warm seas.

Q_S = sensible heat transfer and may be either plus or minus. It is a relatively small quantity in comparison with all the other terms.

Q_A = an advection term and in some areas, such as in the direct path of the Gulf Stream near Ocean Station INDIA (59°N, 20°W), might average 125 calories per square centimeter per day. At Ocean Station JULIET (52.5°N, 20°W) which is out of the direct path of the Gulf Stream, the average is less-about 100 calories per square centimeter per day.

It should be appreciated that the figures given above are subject to wide variation according to locations and circumstances and that the only purpose of quoting them is to provide some general idea of the relative importance of the terms.

Heat budgeting enables a forecaster to have some knowledge of the degree of stratification which exists in the uppermost layers of the sea during the summer months and what changes may occur in the mixed layer in a very short space of time by a change in the weather situation. A marine forecaster will appreciate that this work is very closely allied to the problem of determining how quickly a sea state will be generated by the wind. With experience, he should be able to use heat budgeting to help him formulate answers to both questions of sea state development and the likely changes in the thermal structure of the mixed layer of the ocean at the same time.

9.11 The effects of spray on the evaporation rate. It is evident from the increase in the number of whitecaps, foam, and spray that the evaporation rate increases considerably whenever the wind is blowing over broken water. The broken water may arise from a number of causes, such as a rapid acceleration of the wind speed, a cross sea flowing at an appreciable angle to a swell, or the wind opposing a current. The effect can readily be observed even at wind speeds below five or six meters per second (10-12 knots); hence, if allowance is made for any of these causes, it needs to apply for all wind speeds and not just for winds at gale force and above. In the open ocean, the most common cause is a cross sea running at an angle of more than 45° to a marked swell. When this is so, there is an appreciable difference in the amounts of broken water, and the lumpy appearance of the sea surface makes it a much more difficult matter for an observer to estimate the height of the waves.

In coastal waters, increased evaporation is caused by the wind flowing contrary to the tidal currents. Many meteorologists discount any possibility of a connection between rainfall and the phases of the moon, but there might well be some indirect physical cause as a result of an increase in evaporation near spring tides when tidal currents are running strongly. The legendary connection of rainfall with the phases of the moon might have some substance, therefore, in coastal areas even though it is almost impossible to prove.

Katabatic winds, such as the mistral, also cause a rapid increase in evaporation; the sudden acceleration of the wind wrenches off the tops of the waves before they can acquire appreciable wave lengths and periods. The visual effect gives the appearance of a white sheet being drawn over the sea surface as clouds of spray fill the air. Satellite images over the Gulf of Toulon during a mistral are often of particular interest. Near the coast, the skies are cloudless, and the coastline is distinctly visible. This is to be expected since the mistral is often associated indirectly with the subsidence in an anticyclone over the land. It is noticeable that as the path of the mistral is followed seawards from the coast, the amount of cumulus clouds in the air mass increases and particularly so in the wind channel where the wind speed is greatest. This wind channel is a venturi effect caused by the wind flow from the Rhone Valley.

Such sudden accelerations of wind speed creating quantities of spray are the possible "sparks" which "ignite" hurricanes. Very few of the potentially active areas for tropical storm formation in the tropical seas actually produce a hurricane, even though all the circumstances seem favorable. The probable reason is that the systems generally lack some trigger action to set the hurricane in motion. Prior to the formation of a hurricane the seas are notoriously calm, and the surface temperatures rise to near 30°C in the absence of wind mixing. The formation starts under a batch of towering cumulus and probably with a sudden indraught at the base of these clouds in which the wind will rise to full gale force; the sudden process leading to quantities of spray being projected into the air.

The spray itself could well provide the necessary trigger action, provided heavy rain does not fall immediately afterwards to knock down the seas and eliminate this high potential source of additional energy. Spray could well behave in the same manner as atomized fuel in an internal combustion engine. Once rain starts to fall, it is very noticeable how the sea becomes almost glassy in appearance, once more with a general absence of foam or spray. The quenching effect of rainfall on hurricanes is well known. The actual formation of a tropical storm must certainly be a very sudden process as evidenced by the almost complete lack of observations of actual hurricane formation by ships.

But how important is it to take into account such cases of increased evaporation? In the overall budget and in the terms which make up the oceanic water balance, the circumstances constitute less than 5% of events and therefore are relatively unimportant in this sense. However, there are certain types of storms, and the hurricane is one, in which the energy of the storm is mainly derived from the energy released by the ocean to the atmosphere in the form of latent heat. Hence, models of such storms need to take into account such increased evaporation if they are to operate successfully. In the Mediterranean in particular, during the fall season, convective circulations often develop at middle and high levels in the atmosphere with a vortex extending downwards towards the sea surface. Such storms have relatively unimportant intensity until the vortex actually touches the sea surface and energy is entrained from the warm ocean. The storm then suddenly springs to life, the center deepening rapidly. Autumn storms in the Mediterranean are certainly events to be feared by seamen. But the principle holds generally for gales in autumn, once the seasonal thermocline has begun to erode, and the sea has started to release its store of energy again to the atmosphere. Whether dealing with sea and swell generation or the development of vorticity, the forecaster needs to consider the effects of spray as far as he is able.

9.12 Suggested modifications to existing empirical formulas for evaporation rates. Some suggestions are made for the modification of recognized empirical Dalton type formulas to allow for higher evaporation rates when spray is present. These modifications, which are important in energy exchange problems connected with localized storms such as hurricanes and secondary depressions, are listed below. Much of the additional energy exchange goes to create higher seas, which in turn results in more spray.

It is considered that Laevastu's formula for evaporation,

$$Q_E = 2.46\,(0.26 + .077\,U)\ (0.98\,e_w - e_a), \qquad \text{- - - - (9.2)}$$

is an excellent empirical formula to use for winds up to 30 knots,

where U = the speed of the wind in meters per second,
e_w = the saturated water vapor pressure corresponding to the sea surface temperature,
e_a = the actual water vapor pressure,
Q_E = the heat loss in calories per square centimeter per hour.

The following modification is suggested since it allows for abnormal circumstances when considerable spray is present at higher wind speeds.

$$Q_E = 0.18\,[10 + (U - 6)^{1.1}\,]\,[0.98\,e_w - e_a] \qquad \text{- - - - (9.3)}$$

This formula allows not only for the known change in the behavior of the atmosphere over the oceans at about 6 m/sec (12 to 13 knots), but also for increased evaporation at gale force and above. Up to 30 knots, the figures agree very closely with those given by Laevastu's formula, but they show some increase as the wind approaches 40 knots and substantial increases when winds are of hurricane force.

When the wind blows contrary to a current, some allowance may be made by first increasing the value of the wind speed before insertion of values in the Dalton type formulas (eqtns. 9.1, 9.2, and 9.3). Such an adjustment might indeed be desirable when a cold front moves over the Agulhas Current to the south of the African continent or when a newly formed depression follows a track to the south of the Gulf Stream so that easterly winds oppose the set of the current. The circumstances quoted are for use in areas where depressions deepen rapidly, and much of the energy for the increased vorticity comes from the sea.

It is suggested that if U_c is the average speed of the current derived from a tidal current table or similar source, β is the vector for the set of the current, and α is the wind vector, that a correction can be applied to the wind speed that will compensate for the effects caused by the relationship between the two vectors. Remember, set is the true direction *toward* which the current is flowing, whereas wind direction is the true direction *from* which the wind is blowing (*e.g.,* a current set of 200° flows in direct opposition to a wind from 200°). The following corrections are appropriate:

(a) If the angle between β and α lies between 0° and 45° (*i.e.,* the current set is against the wind or nearly so), add $3U_c$ to the wind speed before inserting in a Dalton type formula.

(b) If the angle between β and α lies between 45° and 135°, add U_c to the wind speed before insertion in the formula.

(c) If the angle between β and α lies between 135° and 180° (*i.e.,* the current set is nearly with the wind or exactly so), subtract $\frac{1}{2}U_c$ from the wind speed..

CHAPTER

10

WAVE STEEPNESS — FORECASTING SLAMMING AND HARBOR BAR CONDITIONS

10.1 Momentum of the sea surface layer. Many factors are involved in the development of waves: the speed and acceleration of the wind, the state of the atmosphere, and the sea surface temperature. But there is another factor which should be taken into account -the existing momentum of the upper layers of the ocean since this has an important bearing on the drag coefficient and the degree of bite that the wind can exercise.

During wave generation, air moving over the surface of the sea at higher velocity than the waves will flow more easily if the surface itself has some velocity in the same direction. But if it has a contrary velocity, the lighter air mass is partially and periodically arrested by impacting the much denser water surface. Momentum is exchanged by a degree of impact. The turbulence in the bottom layer increases, allowing the air mass to get even more bite.

The above explanation may not be entirely adequate, but it serves to explain certain facts observed by seamen such as that gustiness changes with the changing of a tide due to the change of attitude of the wind to the waves. The potential danger of a tidal change is one which is well known to the yachtsman and the small boat fisherman. When a strong wind is blowing with a tide, maneuvering and operating fishing gear, although difficult, may not be impossible. A wind of the same force blowing against the tide will cause the waves to stand up or mushroom and may swamp a small boat. Good seamen take precautions in estuaries and coastal waters where tidal currents run strongly. But this is not solely a coastal problem, and the principles apply equally to the case of currents in the open oceans.

It is important for a forecaster, particularly in closed and semi-closed seas, to remember that wave height increases at a faster rate than wave length irrespective of current flow. The work of Darbyshire has shown that almost all growth of wave height occurs when the fetch is less than 100 miles. This is particularly true in cases of air mass/sea surface temperature classification I (see Chapter 7, Figure 26).

Neither the empirical nor the classical formulas cater to the growth rate adequately and, in particular, do not take into account existing current or tidal flow. Yet the matter can be one of critical importance to small ships, such as trawlers.

10.2 Contrary currents to winds in the Gulf of Alaska. In Chapter 6, the subject of ''holes'' in the ocean was discussed. In particular, reference was made to the Agulhas Bank off the southern shores of Africa where the prevailing wind blows contrary to the Agulhas current over a continental shelf with a pronounced sill, all things combining to make the waters particularly dangerous to shipping. It is not without reason that sailors called the Cape of Good Hope by another name -the Cape of Storms.

Similar circumstances arise in the Gulf of Alaska and along the Aleutian Chain where the damage to ships annually is very high. Depressions moving eastwards over the North Pacific often slow down and deepen in the Gulf, their progress arrested by blocking anticyclones positioned over the land masses to the north and east. This is particularly true in autumn and winter when the continental anticyclones intensify over the frozen land masses. The shape of the Gulf aids the process. The circulations around the depressions that remain and deepen generate and reinforce the counterclockwise flow of surface water northwards along the coast of British Columbia and then westwards along the southern shores of Alaska. This current is an established climatic feature of the general circulation and is reflected in the pattern of the sea surface isotherms. In this area of ocean, current data is based on a relatively few number of observations, and the current atlases need to be improved. Although the average westerly set is only of the order of 1.0 knot for most of the year, the surface flow of water may be accentuated if deep depressions remain almost stationary for several days. A synoptic current is created to reinforce the climatic one.

When such current flow is well extablished any outbreak of cold dry arctic air from off Alaska in winter on the Gulf area will cause the rapid growth of steep waves having short wave lengths. Close to the coast, ice accretion on superstructures and rigging resulting from freezing spray becomes an added hazard, and a ship may suddenly be in considerable danger.

The factors contributing to steep seas have been defined above, but how is the meteorologist who has seldom had training or experience in currents and tides to cope? He would not normally consider taking currents into account in a forecast; no empirical formulas or diagnoses exist to help him. He should derive as much information as is available from current and tidal atlases. If time is available, wind vector diagrams should be kept for fixed positions in the ocean, such as the buoy positions, and from these it can be readily seen by eye how the wind has been blowing relative to the direction of current set over the last week or ten days.

The problem is an urgent one which requires research. When automatic buoy arrays have finally been established in the coastal waters of the Gulf of Alaska, some current data may result which will help resolve the problems and determine the rate of growth of seas in unusual circumstances. Until such time as buoys can supply current data it can only be suggested that forecasters bear this important operational hazard in mind, using with caution the modifications to recognized methods, which will now be suggested.

10.3 Changes in the steepness factor caused by currents or tides and ship's speed. The steepness of the waves is often of far greater interest to the seaman than the mere heights of the waves, and it is important for the seaman to appreciate how steepness will vary with the speed of a current and the speed of the ship relative to the waves. The latter factors are only known aboard the ship and provide one good reason for the mariner himself to understand the problem and undertake some interpretation on board.

A ship steering into incoming seas will meet more wave lengths in any given time interval than she would if either stationary or moving with the waves. This brings about a relative or apparent increase in wave steepness. The effect is very noticeable in a power boat, accelerating away from a beach. The boat soon begins to bounce on the waves.

Similarly, when a current is moving against the sea, an increase in wave steepness results. The relative increases in wave steepness are given in Figure 34 (currents) and Figure 35 (ship's speed). The two effects are cumulative. The graphs represent the fractional increases in steepness due to the speed of the current or the speed of the ship.

Example I - From Figure 34 we see that when a current of 1.5 meters/second (three knots) is flowing opposite to the sea and swell, the steepness of the waves will be increased by approximately 40% in a swell of period 15 seconds and by approximately 70% in a swell of period 10 seconds. In a sea of five seconds, it will be increased at least three or four times, which would almost certainly cause such short period waves to become top heavy and break. Current speeds of 1.5 meters/second (three knots) are not abnormal in tidal waters. Hence, the figures quoted are very realistic. The broken water in any tide rip illustrates the point.

Example II - Similarly, from Figure 35, a ship proceeding at 10 meters/second (20 knots) into a swell of period 15 seconds will experience an apparent increase of steepness of 50%; 70% in seas or swells of 10 second period; and 150% in seas of six second period. Such apparent increases in steepness will affect ships in different ways according to their dimensions. Small ships and power boats would certainly experience slamming as the result of the increase in steepness of the seas, whereas cargo vessels and passenger ships of considerable length might be forced to slow down in longer period swells.

When both factors are present, the product of the two effects results. Thus a ship heading at 15 knots aided by a tide or current of three knots into a swell of period 10 seconds could experience an apparent increase of

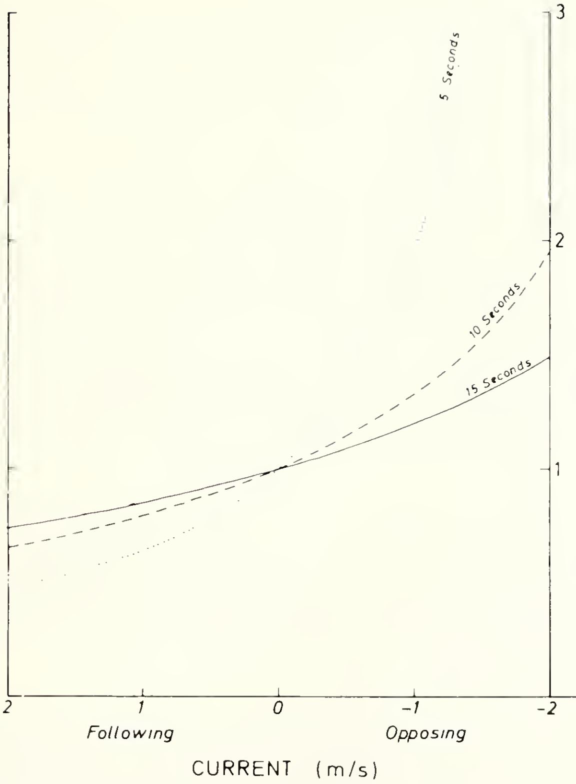

Figure 34 - Effect of current on wave steepness. (From "High Waves in the Agulhas Current" by E.H. Schumann. *Mariners Weather Log,* January 1976).

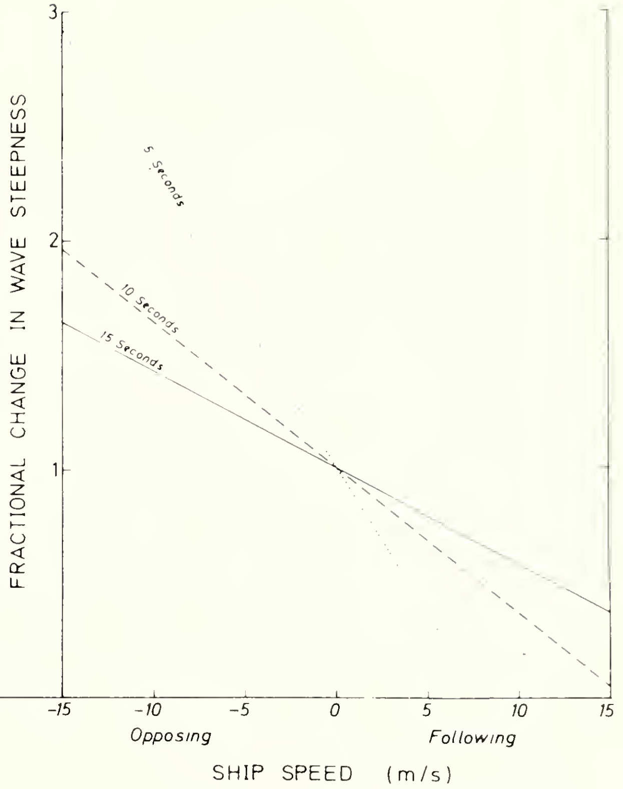

Figure 35 - Effect of ship's speed on wave steepness. (From "High Waves in the Agulhas Current" by E.H. Schumann. *Mariners Weather Log,* January 1976.)

steepness of 1.7 × 1.7 (*i.e.,*almost three times). Such circumstances might arise when a ship emerges from a river mouth or port entrance into an oncoming sea or swell. This could well force the ship to reduce speed to avoid slamming. Wave periods of 10 seconds are not uncommon in open waters; thus, it is an important matter for ships to be aware of the problem and consult current data.

Current and tidal atlases are barely adequate for the purpose, and much available current data remains to be incorporated in them. To some degree, current flow is indicated by features of bottom topography, and there is often considerable difference in the sea conditions experienced in the shallow waters close to the coastline and the deeper waters further to seaward. There is little likelihood that these factors will be incorporated in sea and swell models and so it is important for the seamen to take them into his own considerations of the problem.

10.4 Estuary and harbor bar forecasting. So many boating and fishing tragedies occur each year at holiday times at or near the mouths of river estuaries that the subject merits special comment. To the weather forecaster, who has the task of issuing weather forecasts for such areas, it imposes a special challenge and demands his highest skills and experience as a professional person. Unfortunately, most forecasters seldom receive adequate training to be able to tackle the complexities of such problems. On any shore the marine forecaster, given the aids of synoptic charts, satellite data, and so on, will normally have the capability to make predictions of sea state conditions a few miles offshore before the waves begin to feel bottom. With a little local experience and after some study of the bottom topography, he can usually derive from these data a surf forecast for the beaches sufficient to give holiday makers some indication of when dangerous breaking waves are likely to be experienced. Little more should be expected of him; although this should be a minimal requirement of all weather forecasters engaged in marine forecasting. The problem will receive various degrees of attention by weather services according to the exposure of the coast. In many cases, but by no means all, the greatest impact occurs in temperate latitudes on the westward side of the major continents where there is a long fetch to windward in the westerlies.

But at, or near, the mouths of river estuaries the problems created by surf are considerably increased as a result of the current flow from the river mouth, augmented at certain times of day by the ebb tide. When these act in maximum conjunction at the height of the ebb (or shortly afterwards) and in direct opposition to the onshore movement of seas and swells, in which the steepness of the waves increases automatically with shoaling, the sea state situation may deteriorate rapidly to place small craft in considerable jeopardy. In many instances this is such a localized and specialized problem requiring judgement and experience that the regional weather forecast is only of secondary consideration to the fishermen. But it need not be so, for with good training and some special attention to the problem, marine forecasting services have something to offer to the fishing community, not only to enable them to program sailing times more efficiently, but in the worst circumstances, make a contribution to the safety of boats and men.

The specialized knowledge of the fishermen, the local pilots, and the Coast Guard is not always reflected in the weather forecasts for these areas, and hence, many warnings of dangerous sea state circumstances do not reach the general public. Many weather forecasters might even oppose the suggestion that they be given any responsibility in this matter since the problem is so specialized in its nature and depends considerably on knowledge of river currents, tides, and ship characteristics.* It must be acknowledged that they have some point, for without trainings, the problem can barely be attempted.

10.5 The basic requirements for a sea state forecast at a river mouth. The first requirement is the determination of the maximum speed of the stream due to the combination of current and tide. The speed of many rivers is now controlled by water authorities and such information is often readily available. However, there may be occasions following heavy rainfall or flooding when the river speeds are above normal, and the forecaster will have to use local observations and perhaps exercise personal judgement.

Tidal information for all major ports and secondary ports is found in the *Tide Tables* and is generally sufficient to obtain the times of high and low water and the range of the tide. The proximity to springs or neaps, when tidal effects are near their maximum or minimum, respectively, is also readily available. Specific information on tidal currents is contained in the *Tidal Current Tables,* which are issued for each year. The combination of ebb tide and river current speed may well exceed six knots.

It is a more difficult matter for the forecaster to be up-to-date with the actual flow patterns of the stream in the vicinity of the harbor mouth and over the harbor bar itself, for these are susceptible to continual change and, occasionally, radical alteration following a major storm. Silting is often a considerable problem in these localities requiring channels to be either periodically or regularly dredged. Any major constrictions of the channel due to silting or the deposition of sand or pebbles will cause the maximum current to be augmented in some areas and reduced in others. Generally, the water flow off the entrance results in complex eddy motions for a considerable distance seaward. Sometimes this is plainly seen in satellite pictures, particularly the enhanced infra-red images when the water temperature of the sea and river water have some degree of separation.

The forecaster needs some knowledge of the river and eddy flows, which in most circumstances can be obtained from officials in charge of coastal engineering. If the river traffic is considerable and has major economic significance, it is likely that scale models of the harbor have been constructed to investigate the problems of silting. Familiarization with the results obtained from such models, and some experiments with sea, swell, and wind inputs could prove a tremendous help to a forecaster.

A basic requirement is the latest knowledge of the wave spectra or an estimation of the frequency and height

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**Ed. note: In 1980, routine forecasts for the bar at Grays Harbor, Washington and the mouth of the Columbia River in Oregon were being issued by the NWS.*

distributions in the sea a few miles offshore in deep water before the waves have begun to feel bottom. Once again this is information which will not normally be readily available, and the forecaster will need to deduce it from the latest synoptic charts. In any event, there will be a forecasting task to predict what the conditions will be at the time of the subsequent ebb tide or tides.

The main contribution from the weather forecaster could well be the accurate prediction of the local weather change and particularly the development of a system off the coast which will enhance the onshore flow.

In particular, the forecaster should make allowance for the sea breeze effects in the afternoons, which on certain coastlines of the world can produce appreciable wind speeds for a few hours. If this flow enhances the synoptic flow there will be considerable increase in waves of short period, which are particularly prone to the effects of adverse currents. The effects on ships of large tonnage will not be great, but it will greatly affect fishing vessels and pleasure craft.

10.6 Theoretical considerations. Theoretically, the period T is a conservative quantity (see Appendix A), and we have the equations:

$$T = \frac{L}{C} = \frac{l}{c} \qquad \text{- - - -(10.1)}$$

where C = the speed of the wave in deep water,
L = the wave length of the wave in deep water,
c = the speed of the wave in shallow water,
l = the wave length of the wave in shallow water.

As the waves approach a shore, some refraction takes place, and the speed of the waves decreases as the waves in the rear of a train start to catch up with those in front. This results in more wave energy becoming concentrated into a smaller area. Relatively, the potential energy increases; hence, the wave height tends to increase.

$$\frac{H}{L} = \frac{H}{CT} = \frac{H}{T\sqrt{(gL/2\pi)\tanh(2\pi d/L)}} \qquad \text{- - - -(10.2)}$$

Since we are dealing with the shallow water case, tanh (2πd/L) approximates to 2πd/L. Hence:

$$\frac{H}{L} = \frac{H}{T\sqrt{gd}} \qquad \text{- - - -(10.3)}$$

Equations (10.1), (10.2), and (10.3) will hold generally for coastal waters, but will need some modification at river and estuary entrances where there is an outflowing current or ebb tide of appreciable magnitude.

The period T will not remain conservative, and the general effect will be to cause some increase in the reciprocal value. Waves of short period will be affected more so than the waves of longer period, and the wave lengths will decrease correspondingly.

Hence, if we consider equation (10.3), it is seen that wave steepness is increased for each of the three considerations:

(a) $\frac{1}{T}$ tends to increase, the stronger the opposing current or tide.

(b) H tends to increase as more potential energy is crowded into a smaller area.

(c) $\frac{1}{\sqrt{d}}$ tends to increase as the depth of water decreases.

The ratio of height to wave length will steadily increase until the ratio approaches 1/10. At this ratio, some of the higher waves will be breaking, and theoretically, all should be breaking when the ratio $H/L = 1/7$.

Every entrance poses a different problem on account of the topography, especially the depth of water required over the harbor bar to allow for ready access to shipping. In the case of the Columbia River entrance, the channel is dredged to between 40 and 50 feet. Some rules for forecasting breaking sea conditions for the Columbia River bar have been developed. Those rules appear to work well and could well serve as a model for similar river mouths.

Low level photography of swells approaching the shore or a river entrance can be most instructive and are well illustrated in Plates 7 and 8 of Alsea Bay and Coquille River in Oregon. The short steep breaking waves in the foreground of Plate 7 clearly illustrate the results of the water outflow acting against the incoming swell. There are no jetties, and the sand shifts frequently in an unstable entrance. A small boat with an inexperienced crew could easily be in difficulties in trying to enter or leave this river mouth.

Plate 8 shows clearly that certain areas are more dangerous than others. Note in particular how the waves are breaking on the shores outside the jetties and the confused state of the sea close to the jetty on the right of the picture. The areas in the neighborhood of both jetties are to be avoided as far as possible.

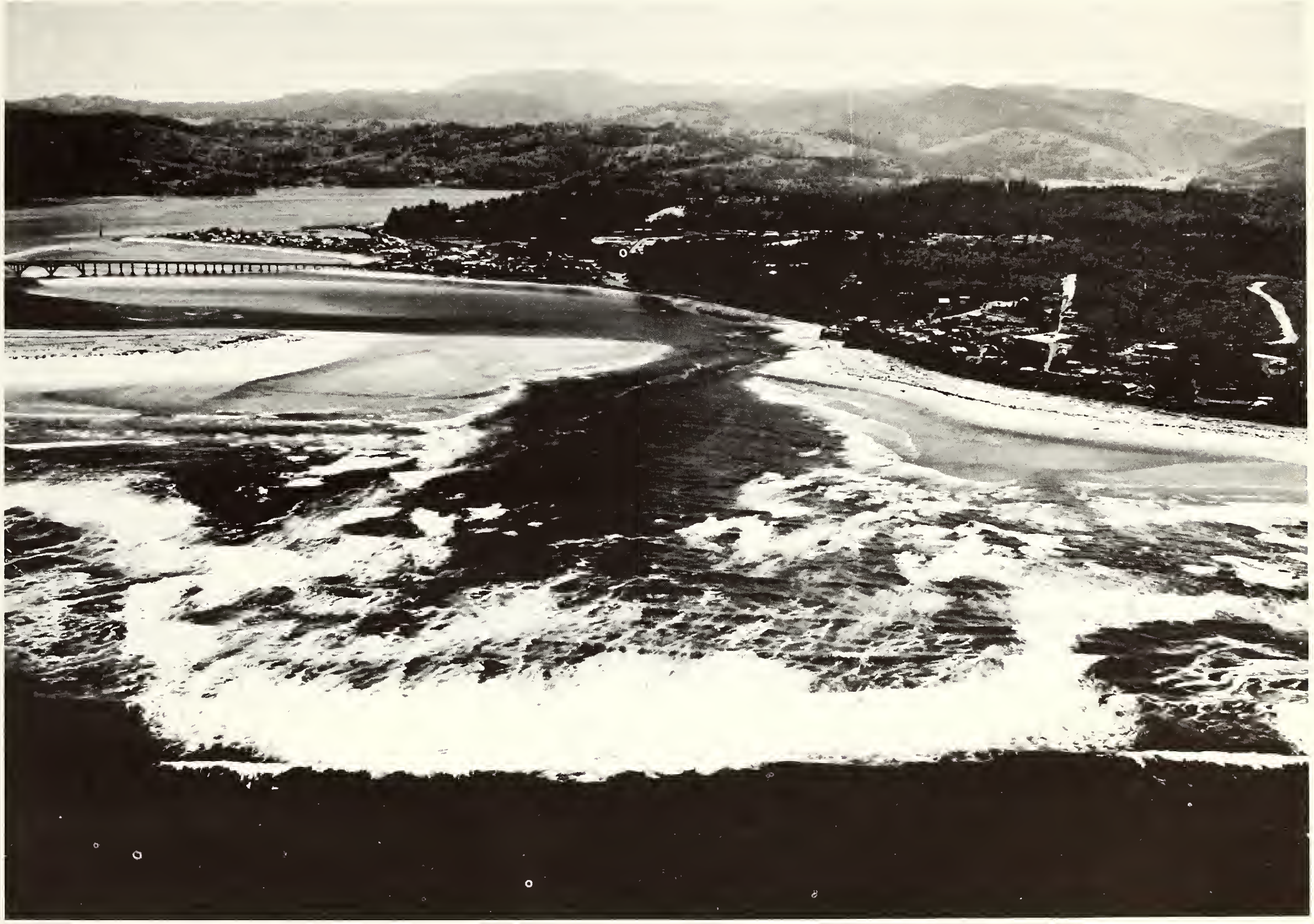


Plate 7 - Wave conditions off Alsea Bay, Oregon. (Photograph courtesy of Oregon State Marine Board.)

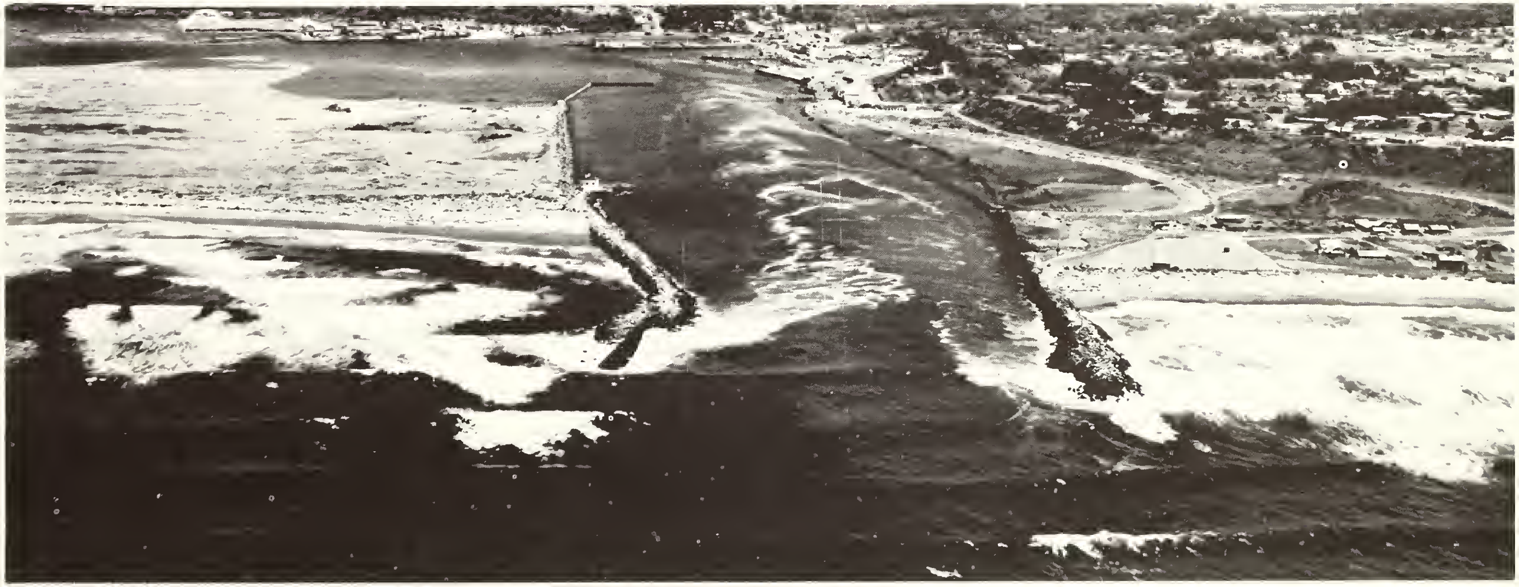


Plate 8 - Wave conditions off Coquille River, Oregon. (Photograph couresy of Oregon State Marine Board.)

CHAPTER

11

WAVE SPECTRA

11.1 Introduction. A deformed sea surface at any moment of time may be considered to be a combination of an infinite number of sinusoidal waves each having a different wave length and period and moving in different directions. At one end of the scale of possibilities are the capillary waves with a wave length of only an inch or two with periods of a fraction of a second, and at the other end there may be giant swells with wave lengths of several hundred feet and periods of up to 20 seconds. Theoretical considerations set an upper limit of about this order for deep water waves (see Appendix A).

A wave of period 20 seconds will have a wave length in excess of 2,000 feet, and only in exceptional circumstances have wave lengths of ½ mile been noted in the southern oceans where the fetch can be almost unlimited.

In any given sea, although the range of possibilities is infinite, certain wave lengths will predominate. In other words, the energy is mainly concentrated into frequency bands. When making any measurement or assessment the objective is to identify the main frequency (or wave period) present; although there will occasionally be more than one such period, as for example when sea can be clearly distinguished from swell.

Each wave makes an energy contribution according to its amplitude. The main feature that a user wishes to know is the total energy content since this is some measure of the capacity of the sea to damage or destroy a ship. From a knowledge of the total energy content, E, useful derivatives, such as the significant wave height and corresponding period, can be readily obtained. But furthermore, it is desirable to know how the energy is concentrated within certain frequency bands.

This information can be deduced from the spectral analyses of wave traces recorded by wave-rider buoys or wavemeters. A typical wave trace from one of these recorders was given in Chapter 2 (Figure 1). The type of spectral diagram deduced from this graph will now be discussed in more detail.

11.2 The energy spectra. From analysis of a wave trace of a deformed sea surface it is possible to determine a mean height (or energy combination) corresponding to any given period (or frequency), and a plot can then readily be made of frequency against the product of E and the period T. This results in a typical graph form shown in Figure 36. An approximation to the area under the graph may be obtained from the sum of the areas of the rectangles; each one of which is proportional to the square of the height of a sine wave corresponding to the frequency.

The area under the graph, called an energy spectral diagram, will represent the energy content in the displaced surface. In a fully developed sea, the area under the graph is a function of the wind speed. The higher the wind speed the greater the total amount of energy tranferred to the ocean. Hence, we can compute a different energy spectral graph corresponding to any particular wind speed for a fully developed sea. In Figure 37, three typical graphs are shown corresponding to wind speeds of 20, 30, and 40 knots.

In the 20 knot graph, the maximum occurs at point A, corresponding to a frequency of 0.12 per second or a period of about eight seconds; at 30 knots it occurs at B at frequency 0.08 per second corresponding to a period of about 12.5 seconds; at 40 knots it is point C at frequency 0.06 per second corresponding to a period of about 16.5 seconds. *The higher the wind speed, the higher the proportion of energy devoted towards creating waves*

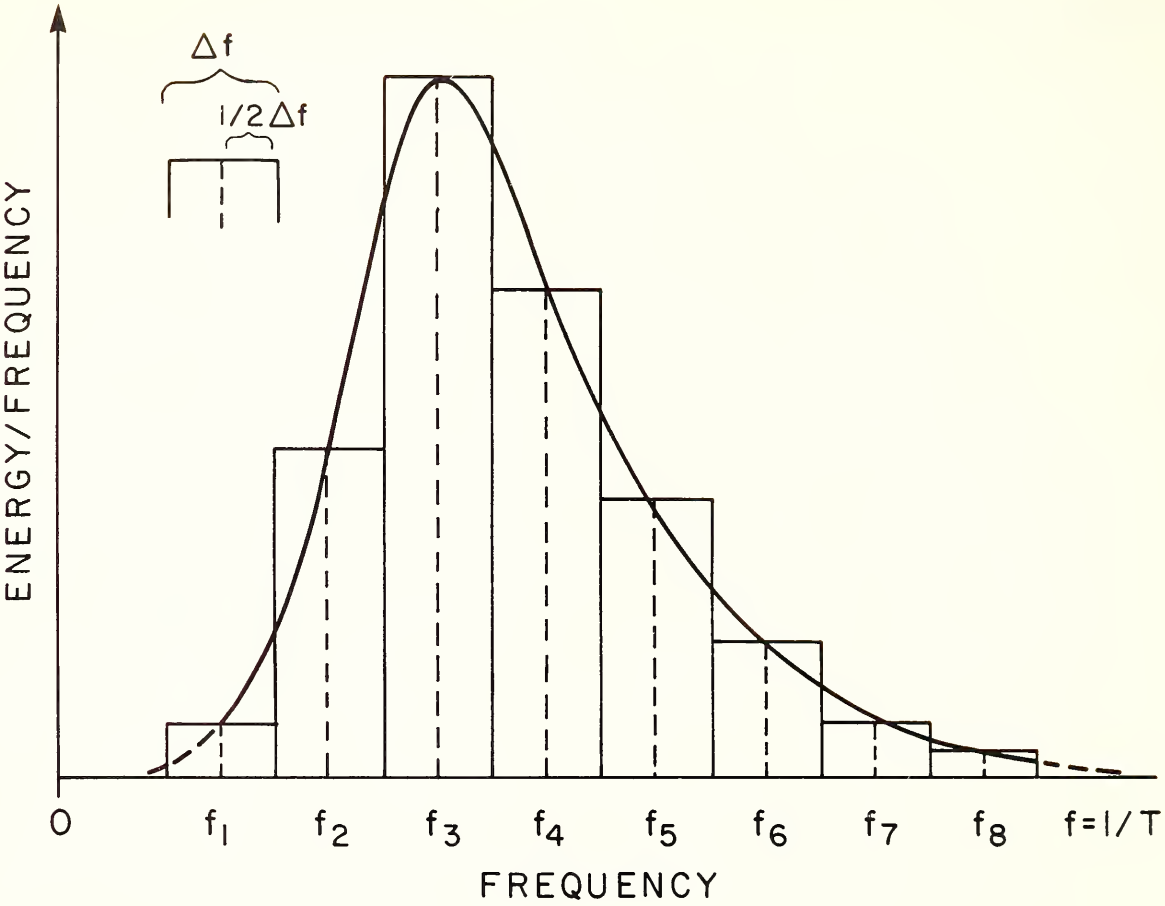


Figure 36 - Wave spectrum.

of low frequency or long period. The diagrams illustrate why winds of less than 20 knots will not produce waves of great height, the energy being comparatively evenly spread over a broad band of frequencies.

In dealing with the practical problem, there are usually constraints of duration and fetch to consider, and the problem facing the forecaster is to determine how far conditions can develop before the circumstances change. Nevertheless, it is always useful to know what would be the maximum conditions generated for any wind speed if circumstances allowed. These are listed in Table 9.

Similarly it is always useful to know how the energy is theoretically distributed in a spectrum. Statistically, it is possible to derive a distribution of the wave heights for any specified value of E. Heights will be proportional to the square root of E. The distribution relative to heights is listed in Table 10.

The greatest height observed will depend on all components coming into precise phase and conjunction exactly at the same time. The more waves that are observed the greater the chance of this happening. Generally, an observer in making an observation will not have time to observe more than 100 waves.

11.3 Basic interpretations from spectral energy curves. Let us now consider a typical spectral energy curve derived from the wave meter traces (see Figure 38). The ordinates are the frequency (f = 1/T) and S(f), which represents the ratio of the energy content to the corresponding frequency. Since the energy is *proportional* to

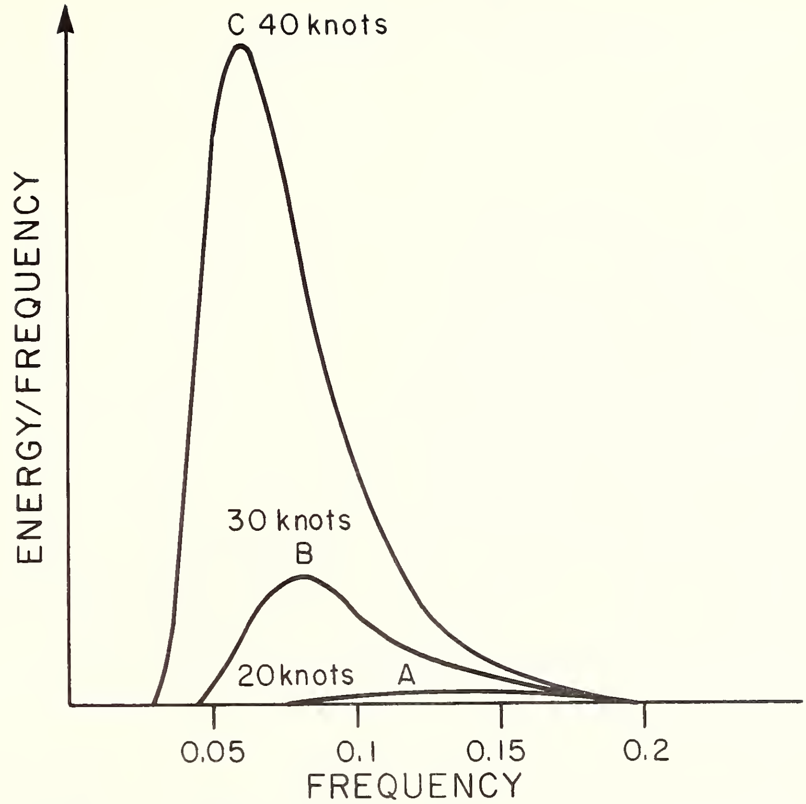


Figure 37 - Continuous wave spectrum for fully arisen seas at wind speeds of 20, 30, and 40 knots. Note some displacement of the peaks represented by points A, B, and C from higher towards lower frequency with increasing wind speed.

TABLE 9

MAXIMUM PERIOD OF THE DOMINANT BAND IN THE SPECTRUM WHERE HIGHEST PROPORTION OF ENERGY IS CONCENTRATED

Wind Speed (knots)	Frequency	Maximum period (seconds)	Square of period	Approximate Corresponding wave length (feet)	
				(feet)	(meters)
10	0.248	4.0	16.0	81.9	25.0
15	0.163	6.2	37.8	193.8	59.0
20	0.124	8.1	65.6	336.0	102.5
25	0.099	10.1	102.0	522.3	159.2
30	0.0825	12.1	146.4	749.6	228.5
35	0.0707	14.2	200.2	1025.1	312.5
40	0.0619	16.2	262.4	1343.7	409.6
45	0.0549	18.2	331.2	1695.9	516.9
50	0.0495	20.2	408.0	2089.2	636.8
55	0.0449	22.3	495.1	2534.7	772.5
60	0.0412	24.3	590.5	3023.3	921.5

TABLE 10

USEFUL SPECTRAL INFORMATION

	feet	meters
Most frequent height	$= 1.41\sqrt{E}$	$= 2\sqrt{E_1}$
Average height	$= 1.77\sqrt{E}$	$= 2.5\sqrt{E_1}$
Significant height	$= 2.83\sqrt{E}$	$= 4\sqrt{E_1}$
Average height of highest 1/10 highest waves	$= 3.60\sqrt{E}$	$= 5.1\sqrt{E_1}$
10% of waves are higher than	$= 3.04\sqrt{E}$	$= 4.3\sqrt{E_1}$

Approximately one in eight waves has an amplitude less than $0.70\sqrt{E}$.

Approximately one in eight waves has an amplitude greater than $4\sqrt{E_1}$, the significant wave height. One in eight has an amplitude less than $\sqrt{E_1}$.

Data for fully developed seas

Wind Speed (kn)	f_{max}	T_{max}	E	$\sqrt{E}$	$H_{1/3}$ (feet)	E_1	$\sqrt{E_1}$	$H_{1/3}$ (meters)
10	0.248	4.0	0.24	0.49	1.39	0.011	0.106	0.42
12	0.206	4.9	0.60	0.77	2.19	0.028	0.167	0.67
14	0.177	5.6	1.30	1.20	3.23	0.061	0.256	0.98
16	0.155	6.5	2.54	1.6	4.51	0.118	0.344	1.35
18	0.138	7.2	4.60	2.1	6.07	0.214	0.463	1.85
20	0.124	8.1	7.7	2.8	7.85	0.358	0.598	2.39
22	0.113	8.8	12.5	3.5	10.0	0.581	0.762	3.05
24	0.103	9.7	19.3	4.4	12.4	0.900	0.947	3.79
26	0.095	10.5	28.8	5.4	15.2	1.339	1.157	4.63
28	0.088	11.4	41.6	6.4	18.3	1.935	1.391	5.56
30	0.083	12.0	58.8	7.7	21.7	2.734	1.654	6.61
32	0.077	13.0	81.2	9.0	25.5	3.776	1.943	7.77
34	0.073	13.7	110.0	10.5	29.7	5.115	2.26	9.05
36	0.069	14.5	146.3	12.1	34.2	6.803	2.61	10.43
38	0.065	15.4	191.7	13.9	39.2	8.915	2.99	11.94
40	0.062	16.1	247.8	15.7	44.5	11.52	3.39	13.58
42	0.059	16.9	316.3	17.8	50.3	14.71	3.84	15.34
44	0.056	17.9	399.1	20.0	56.5	18.56	4.31	17.23
46	0.054	18.5	498.4	22.3	63.2	23.18	4.81	19.28
48	0.052	19.2	616.6	24.8	70.3	28.67	5.35	21.42
50	0.050	20.0	756.3	27.5	77.8	35.17	5.93	23.72
52	0.048	20.8	920.1	30.3	85.8	42.18	6.54	26.16
54	0.046	21.7	1111.2	33.3	94.3	51.67	7.19	28.75
56	0.044	22.7	1332.8	36.5	103.3	61.98	7.81	31.49
58	0.043	23.3	1568.3	39.7	112.5	72.93	8.54	34.16

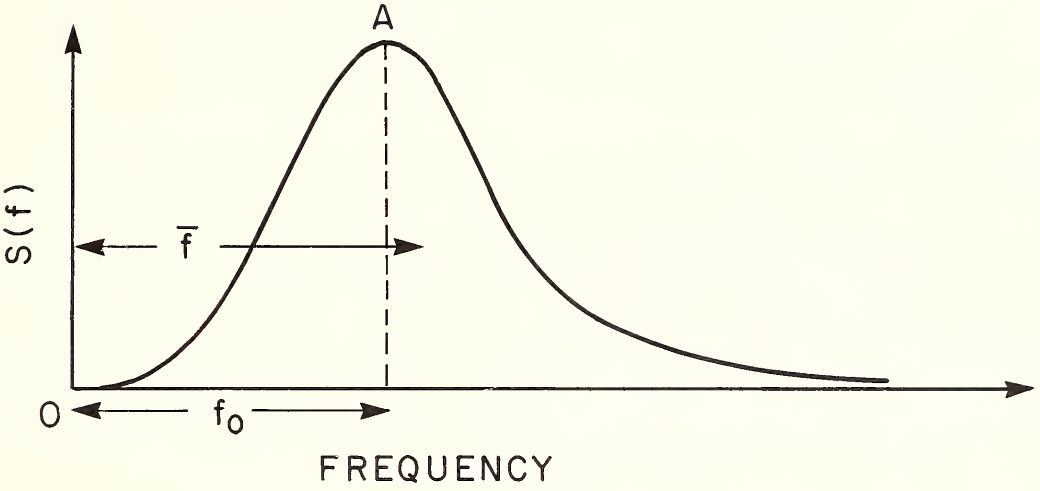


Figure 38 - Typical spectral energy curve.

the sum of the squares of the displacements (ΣH^2) from the mean position, the dimensions of the function S(f) as plotted in Figure 38 will be L^2T* where L is length and T is time. A few additional terms that were dropped have to be included if the actual energy content to corresponding frequency is to be computed.

The area under the curve may be expressed in mathematical form and will represent the total energy in the deformed sea surface:

$$E = \int_0^\infty S(f)df \qquad \text{---- (11.1)}$$

If the coordinates corresponding to the frequencies are known, the area under the curve can be derived in many ways, such as by applying Simpson's rule for calculating an area, although a simple sum of the ordinates is usually quite sufficient. This approximately the same as summing the areas of the rectangles shown in Figure 36.

11.4 The significant wave height. Knowing E, it is possible to deduce the significant wave height, $H_{1/3}$, since this is directly proportional to the square root of E. Experience has shown that $H_{1/3}$ corresponds closely with the wave height most frequently reported by trained observers. For practical operations, the following two equations give close approximations for the significant wave height:

$$H_{1/3} = 4\sqrt{E} \text{ (meters)} \qquad \text{-----(11.2)}$$

$$H_{1/3} = 2.83\sqrt{E} \text{ (feet)} \qquad \text{-----(11.3)}$$

It can also be shown that among the various definitions of wave heights, the significant wave height is the most statistically stable one.

Ed. note: It is shown in the appendix that the **energy per unit area** *of a surface wave is* $E = (\rho g H^2)/8$ *where* ρ *is water density, g is acceleration of gravity, and H is wave height. Thus, when all the terms are considered, S(f) has the dimensions* ML^2T^1 *where M is mass, L is length, and T is time. The common practice is to drop the term* ρg*; it being understood that the energy is for a unit area.*

Although a knowledge of E is the most important parameter needed for practical applications, it is almost equally important to know how the energy is distributed relative to the frequencies (or periods). Thus, we saw from Figure 37 that in a fully developed sea corresponding to a wind speed of 20 knots, the energy was fairly evenly distributed in a band of frequency from .03 to 0.20 with the maximum at about 0.12. At higher wind speeds the energy became far more concentrated into wave bands at lower frequencies.

11.5 The significant wave period. In a similar way, it is necessary to have some agreed definitions for wave periods corresponding to such height measurements as $H_{1/10}$, $H_{1/3}$, and $\overline{H}$. Simple consideration of Figure 39 shows that f_{max} (also f_0) is not the same as $\overline{f}$, the mean frequency. The observer at sea has been shown to assess heights from the highest one third of waves observed, which approximates closely to the statistically defined "significant wave height." The observer does not necessarily measure the corresponding period.

In the analysis of a wave trace, such as illustrated in Chapter 2 (Fig. 1), the average period might be conveniently assessed from the intervals between the zero up-crossings on the wave trace. The zero up-crossing wave period calculated by statistical methods (see paragraph 11.6c) gives an average apparent period and requires a correction of about 20% to the average obtained from the spectral diagram. Among the various definitions of wave periods, *the significant wave period is the most statistically stable one* and can be estimated by the relationship:

$$T_{1/3} = T_p/1.05 \qquad \text{-----(11.4)}$$

where T_p or T_{max} is defined as the peak period.

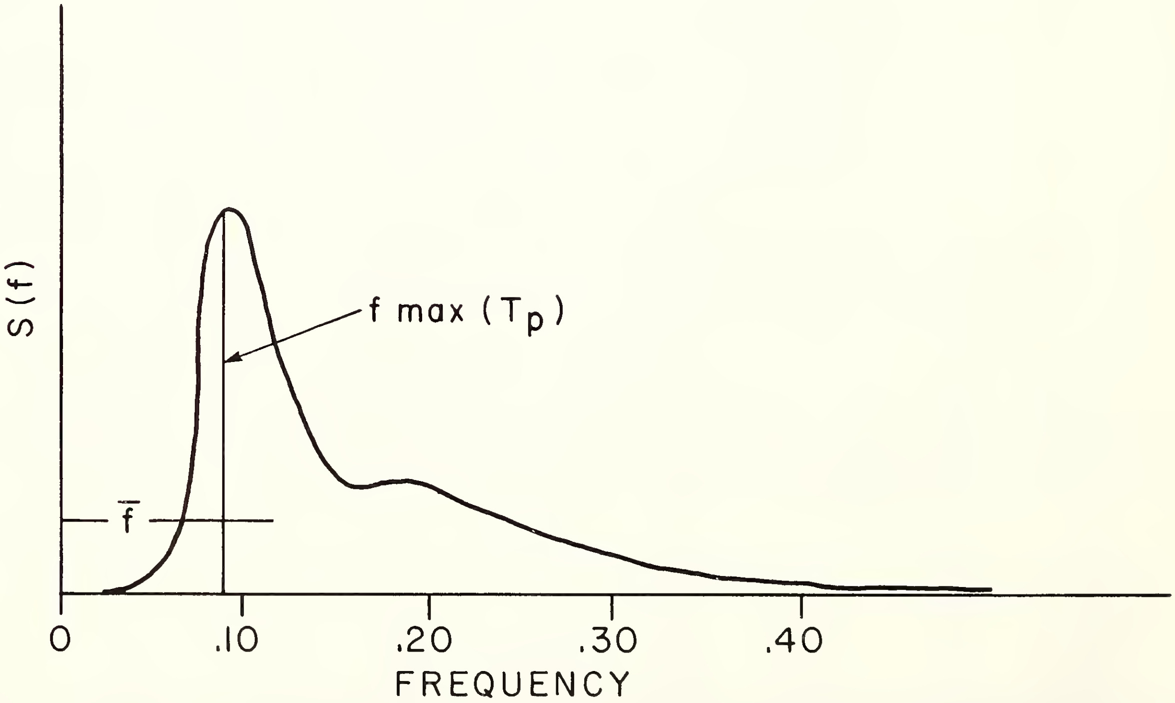


Figure 39 - Wave spectrum diagram.

From a spectral data message, it is usually a relatively easy matter to assess f_{max} from the plotted data or occasionally, by inspection. The reciprocal gives the corresponding T_{max} which should be reduced by between

5% and 10% to obtain the significant wave period depending on whether there are other obvious maxima in the spectral data at shorter periods. The derived value can be assumed to be the significant period and should be the one used for obtaining an assessment of the average wave length. We can estimate wave length if we know the period by using the following equation, which is developed in the appendix:

$$L \cong 5.12\ T^2$$

where L = wave length in feet,
5.12 = constant with the proper dimensional units L/T^2,
T = period in seconds.

A whole range of frequencies are present in any given sea state, and it is only possible to talk realistically of specific periods when dealing with fully arisen seas at the higher wind speeds.

11.6 Further statistical interpretations of spectral energy diagrams. Other useful statistical derivatives of spectral energy diagrams may be obtained by considering the integrals of the form:

$$I_n = \int_0^\infty f^n S(f)df \quad \text{where } n = 0, 1, 2, 3, \text{etc.}$$

For $n = 0$, $I_0 = \int_0^\infty S(f)df = E.$

For $n = 1$, $I_1 = \int_0^\infty fS(f)df = \bar{f}\ E.$

$$\text{Hence, } \bar{f} = I_1/I_0. \qquad \text{-----(11.5)}$$

We can derive a mean frequency, $\bar{f}$, of the spectrum from I_1/I_0.

For $n = 2$, $I_2 = \int_0^\infty f^2 S(f)df.$

For $n = 3$, $I_3 = \int_0^\infty f^3 S(f)df.$

For $n = 4$, $I_4 = \int_0^\infty f^4 S(f)df.$

The following meaningful parameters may be derived from a knowledge of I_0, I_1 . . . I_4.

(a) A measure of the skewness of the curve is given by

$$B = \frac{I_3}{(I_2)^{3/2}} \qquad \text{-----(11.6)}$$

(b) A parameter which measures the band width of frequencies in which maximum energy is concentrated is given by

$$G = \text{Spectral width parameter} = \sqrt{1 - (I_2)^2/I_0 I_4} \qquad \text{-----(11.7)}$$

(c) The average apparent period can be derived from

$$\sqrt{I_2/I_4} \qquad \text{----(11.8)}$$

(d) A measure of the steepness of the waves may also be derived from a knowledge of these integrals. Obviously, it will be most useful to know the steepness corresponding to those waves of frequency which have maximum concentration of energy.

Some measure of this is given by $\frac{H_{1/3}}{L_O}$, where L_O is the wave length corresponding to the maximum spectral ordinate. From this, a useful parameter, j, may be defined for steepness.

$$j = \sqrt{L_O/39.3H_{1/3}} \qquad \text{-----(11.9)}$$

The above statistical quantities are all useful measures which help to define the main characteristics in any given wave spectral diagram, but in general, the user can only derive such quantities with the aid of a computer. Certainly, such facilities are not available to the seaman on board ships at the present time, and weather offices ashore can only derive such information if they have computer facilities that can be supplied with the raw data in total. The form of the spectral data messages will now be given, and it will be shown that much useful information can be derived from it from examination by eye and particularly so if a sequence of such messages is studied in combination with the surface synoptic charts.

11.7 Messages of spectral energy data from buoys.* It is usual to transmit the data received from buoys in a direct form. The data content of the messages follows a few groups which give the position of the buoy, the date, the time of the observation, and the significant wave height and period.

The form of message has varied slightly, but the following is a typical example received from the buoy, EB03, positioned at 56°N 147.9°W on 22 February 1975 at 0000 GMT:

EB03 //560 71479 1000/

10000	20000	30000	40000	51001	61971	71062	82602	93022	02252
11322	29751	38501	46031	53821	62331	71601	81241	91261	01471
11361	21011	37170	46620	55780	64650	75550	86240	95780	04830
14160	23830	33110	42860	53790	63600	72180	81760	92180	01920
11290	27975	36585	48155	59605	69505	71110	81140	97525	05555

Values of frequency are derived from an interpretation of the first digit in any group. In the first line, frequencies go from .01 to .10. Thus, the eighth group starts with 8 and implies a frequency of .08. If the group falls in the second line, the frequency lies between .11 and .20. Thus, the eighth group in the second line (81241) refers to a frequency of .18.

The next three figures in each group indicate the corresponding spectral density value in meters²/Hz with the value of the last digit indicating where a decimal point should be placed. Thus, 2482 would indicate a value of 24.8 whereas 2480 would be 0.248. The detail provided by the message is set out fully in Table 11.

**Ed. note: The spectral data format has been changed since 1977. The most recent format as of September 1980 is in Appendix C.*

TABLE 11

WAVE SPECTRAL INFORMATION FROM EBO3, 0000GMT, 22 FEBRUARY 1975

Freq.	S(f)	Freq.	S(f)	Freq.	S(f)	Freq.	S(f)	Freq.	S(f)
.01	0	.11	13.2	.21	1.36	.31	0.416	.41	.129
.02	0	.12	9.75	.22	1.01	.32	0.383	.42	.080
.03	0	.13	8.50	.23	0.717	.33	0.311	.43	.066
.04	0	.14	6.03	.24	0.662	.34	0.286	.44	.081
.05	1.00	.15	3.82	.25	0.578	.35	0.379	.45	.096
.06	1.97	.16	2.33	.26	0.465	.36	0.360	.46	.095
.07	10.60	.17	1.60	.27	0.555	.37	0.218	.47	.111
.08	26.00	.18	1.24	.28	0.624	.38	0.176	.48	.114
.09	30.20	.19	1.26	.29	0.578	.39	0.218	.49	.096
.10	22.50	.20	1.47	.30	0.483	.40	0.192	.50	.055

The spectral energy diagram is shown plotted in Figure 40. The scale has been increased tenfold from frequency 0.15 Hz upwards. Most of the energy is concentrated at the lower end of the frequency scale. If the same scale were used throughout, the detail at higher frequencies would be missed.

It can be seen from Figure 40 that the main peak occurs at peak "A"-frequency 0.09 (corresponding to a period of 11.1 seconds); there are other peaks of frequency at "B"-frequency 0.20 (period 5.0 seconds) and at "C"-frequency 0.28 (period 3.6 seconds). There is a fourth frequency at "D"-frequency 0.35 (2.9 seconds).

By summing the ordinates, an estimate of the area under the curve can be readily obtained; the total comes to 152.36. Multiplying this figure by frequency interval of .01 gives the value of E, and from this we see that the significant wave height is $4\sqrt{1.5236}$ or 4.94 meters. The significant wave period is obtained by reducing the

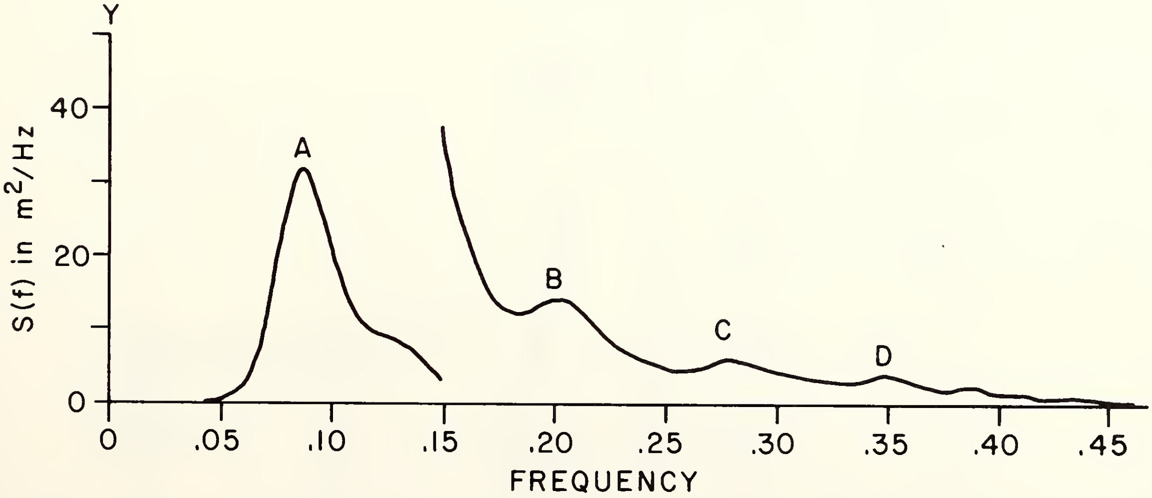


Figure 40 - Spectral graph at EB03,0000 GMT, 22 February 1975.

maximum period of 11.1 seconds by about 5% to give a value of 10.5 seconds.

There are several distinct peak frequencies in Figure 40. The main peak was probably due to a swell with a corresponding wave length of 5.12 x $(10.5)^2$ feet or approximately 560 feet. Peaks B and C were probably mainly attributable to seas developing into swells and peak D to the local sea effect. It is possible, therefore, to define other notable corresponding wave lengths of approximately 128, 66, and 43 feet. Such treatment is largely academic, but it can be inferred that certain combinations of waves will produce high waves of short wave lengths with strong tendency to break.

A measure of the steepness of the wave is given by the ratio $H_{1/3}/L_O$. L_O is the wave length corresponding to the peak frequency of 11.1 seconds and equals 5.12 x $(11.1)^2$ or 631 feet (192 meters).

The ratio is 4.94/192, which is approximately 1 in 39. Swells of this order are in no danger of breaking.

The center of gravity of the area, that is, the mean frequency can be calculated using equation (11.5) and values from Table 11.

$$\overline{f} = \frac{I_1}{I_0} = \frac{\int_0^{\infty} fS(f)df}{\int_0^{\infty} S(f)df} \cong \frac{\Sigma f_n S(f)_n \Delta f}{\Sigma S(f)_n \Delta f} \qquad \text{----(11.10)}$$

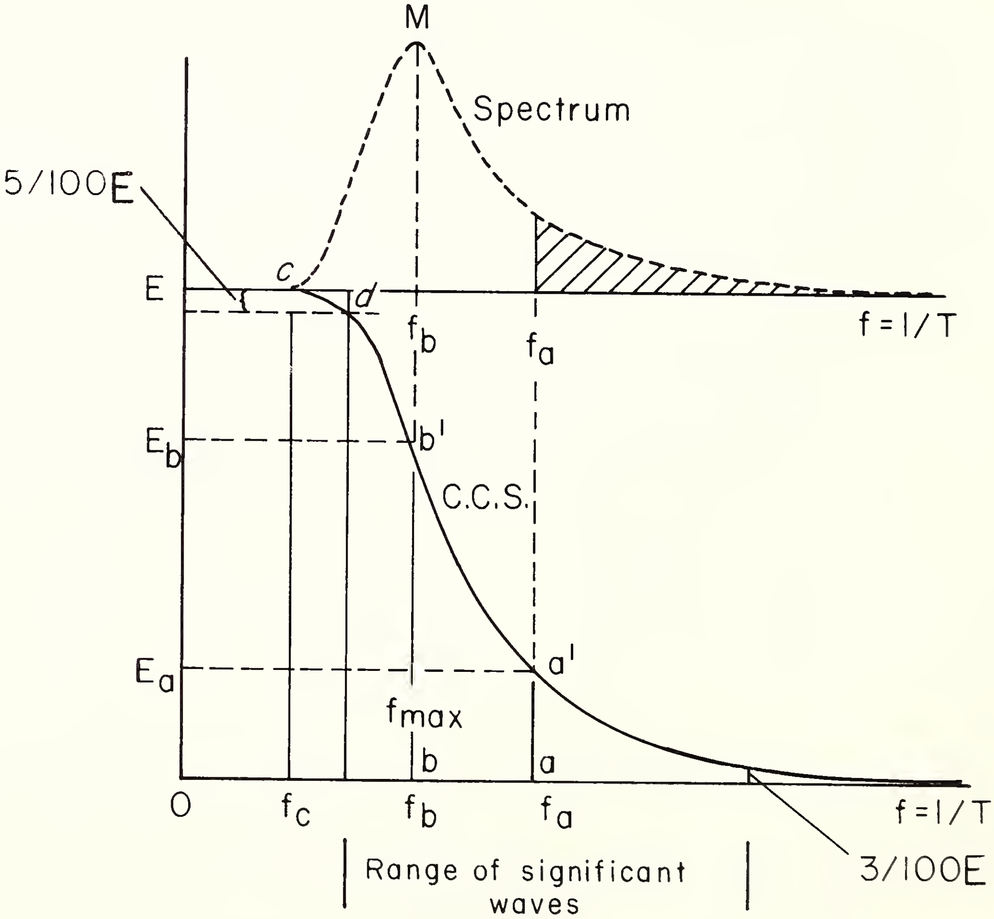


Figure 41 - Co-cumulative spectrum. (From *Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics.* H.O. Pub. No. 603.)

where (f_1 = .01, f_2 = .02, ...f_{50} = .50), Δf = .01, and ($S(f)_1$ = 0, $S(f)_2$ = 0, . . . $S(f)_{50}$ = .055). Note that I_O = 1.5236. Upon doing the calculation, we determine that $\overline{f}$ = 0.116 H_Z from which $\overline{T}$ = 8.6 sec. and $\overline{L}$ = 379 feet.

11.8 Co-cumulative spectra. In practical wave forecasting it is sometimes more convenient to use graphs of the quantity E (the energy content) plotted against the frequency f.

Such graphs, called co-cumulative spectra, can be readily derived from the spectral graphs by summing the amounts of energy from the higher frequencies to zero. The upper portion of Figure 41 shows a typical energy spectral diagram corresponding to a given situation. The shaded area represents the amount of energy in the wave spectrum for the range of values greater than f_a and is represented by the ordinate aa' in the lower graph.

11.9 The properties of the co-cumulative power spectra. Since, in this type of graph, E is plotted directly against frequency, the procedure of cutting out unwanted parts of the wave spectrum can more readily be achieved. Also, the frequency where the maximum amount of energy is concentrated can very easily be deduced from the point where the slope of the curve is greatest. At a certain point at the lower end of the frequency scale the curves level off rapidly to a value which corresponds to the energy of a fully developed sea. Curves for a fully developed sea are plotted for every two knots of wind speed; energy units, E, are in ft^2. These curves are contained in the U. S. Naval Oceanographic Office publications, *Practical Methods for Observing and Forecasting Waves by Means of Wave Spectra and Statistics* (H.O. publication no. 603).

In most practical work, there is either a limitation of fetch or duration, and ships seldom experience a fully developed sea. Co-cumulative spectral graphs based on fully developed seas corresponding to particular wind speeds have been in use for some years. They are not reproduced here since there is some question as to the accuracy of the constraint lines. In addition, it is considered that the approach to practical problems by co-cumulative spectra is seldom as effective as the use of sequences of spectral graphs at three or six hourly intervals, which have now become available as a result of the environmental buoy program. In considering sequential diagrams, it may occasionally be advatageous to construct a co-cumulative spectrum since comparison be-

TABLE 12

MINIMUM FETCH AND MINIMUM DURATION NEEDED TO GENERATE A FULLY DEVELOPED SEA FOR VARIOUS WIND SPEEDS

Wind Speed (kn)	Minimum fetch (naut. miles)	Minimum duration (hours)
10	10	2.4
12	18	3.8
14	28	5.2
16	40	6.6
18	55	8.3
20	75	10
22	100	12
24	130	14
26	180	17
28	230	20
30	280	23
32	340	27
34	420	30
36	500	34
38	600	38
40	710	42
42	830	47
44	960	52
46	1100	57
48	1250	63
50	1420	69
52	1610	75
54	1800	81
56	2100	88

tween a wave spectrum and a spectrum for a fully developed sea enables the forecaster to obtain some idea of the degree to which the sea and swell has progressed towards the fully developed state. It further enables him to estimate how much further development is possible, assuming the wind speed does not decrease.

Table 12 gives the minimum fetch length (or the corresponding minumum number of hours required) for any steady wind speed to generate a fully arisen sea. They are necessarily average values applying mainly to stable atmospheric conditions and do not take into account the properties of the air mass or the water.

Information, such as that given in Table 12 which applies to fully developed seas, can be misleading to a forecaster. Limitations of fetch and duration mean that fully developed seas are seldom experienced, but breaking wave conditions—circumstances which are particularly adverse to shipping—may occur long before the seas are approaching the fully-developed stage.

It is for this reason that spectral diagrams are best used in practical applications in their basic form rather than in co-cumulative form. As in synoptic chart work for monitoring the weather, the changes and the rates of change are derived from sequential analysis, and the presentation needs to be such that detail is not concealed in any way.

CHAPTER

12

THE USE OF WAVE SPECTRAL DATA IN MARINE SYNOPTIC ANALYSES

12.1 Introduction. Sequence analysis of wave spectral data will be discussed in this chapter to illustrate its use in practical work.

Data collected from EB03 (56 °N 147.9 °W) and from special projects at Ocean Weather Station INDIA in the North Atlantic (59 °N 20 °W) and Ocean Weather Station PAPA in the North Pacific (50 °N 145 °W), will be considered.

Data from these special projects are seldom collected routinely and consequently, do not cover a sufficient period of time to allow sound judgements to be made on seasonal variations of sea and swell. Nevertheless, they constitute a valuable series of measurements that allow some comparisons to be drawn between stations. In particular, a comparison between data at Ocean Station PAPA and Ocean Weather Station INDIA is valuable in view of the similarity of positions in the respective oceans (the Pacific and the Atlantic). They are in the eastern half of each ocean, and the centers of many depressions pass sensibly close by on the northern side. A few centers pass to the south; hence, both stations experience winds from all quarters.

The prevailing winds lie between west and southwest where there are long fetches exceeding 1,500 miles, thus providing the opportunity for fully developed seas. Both stations have a fairly limited fetch of the order of 500 miles in the sector between northwest and north in the direction of either an ice edge or a land mass.

12.2 Spectral diagram sequences from buoy reports.

(a) *Spectral data from EB03—21-22 February 1975.* Although much useful statistical information can be obtained from the analysis of a single spectral diagram, such as described in the last chapter, greater practical value often results from an examination of a regular sequence considered in conjunction with the surface synoptic chart sequences. Usually, a forecaster has buoy data available that is transmitted every three hours and surface synoptic charts every six hours.

In illustration, a sequence has been selected using the three-hourly reports from EB03 for 21 February 1975. The spectral data are listed in Tables 13 and 14, and some of the spectral data for 21 February is plotted in Figure 42. The ordinates are multiplied tenfold for frequency values greater than 0.16. The corresponding surface synoptic charts are to be found in Chapter 15.

Reference to these charts will show that a deep depression of 957 millibars was rapidly approaching the Gulf of Alaska from the southwest at 0000 GMT. The center at that time was over 300 miles from the buoy, which was experiencing comparatively warm stable southeast winds. The spectral data (see Figure 42) shows little or no evidence of swell at 0000 GMT, but there are signs of local seas of increasing magnitude having frequencies of 0.23 and 0.28, corresponding to periods of 4.4 and 3.6 seconds respectively. The waves of period 4.4 seconds are much more pronounced on the 0300 GMT report, and there is one slight evidence of a developing swell. A movement towards lower frequencies is clearly evident.

The 0600 chart shows the center to be considerably nearer to the buoy and the central pressure having fallen a

TABLE 13

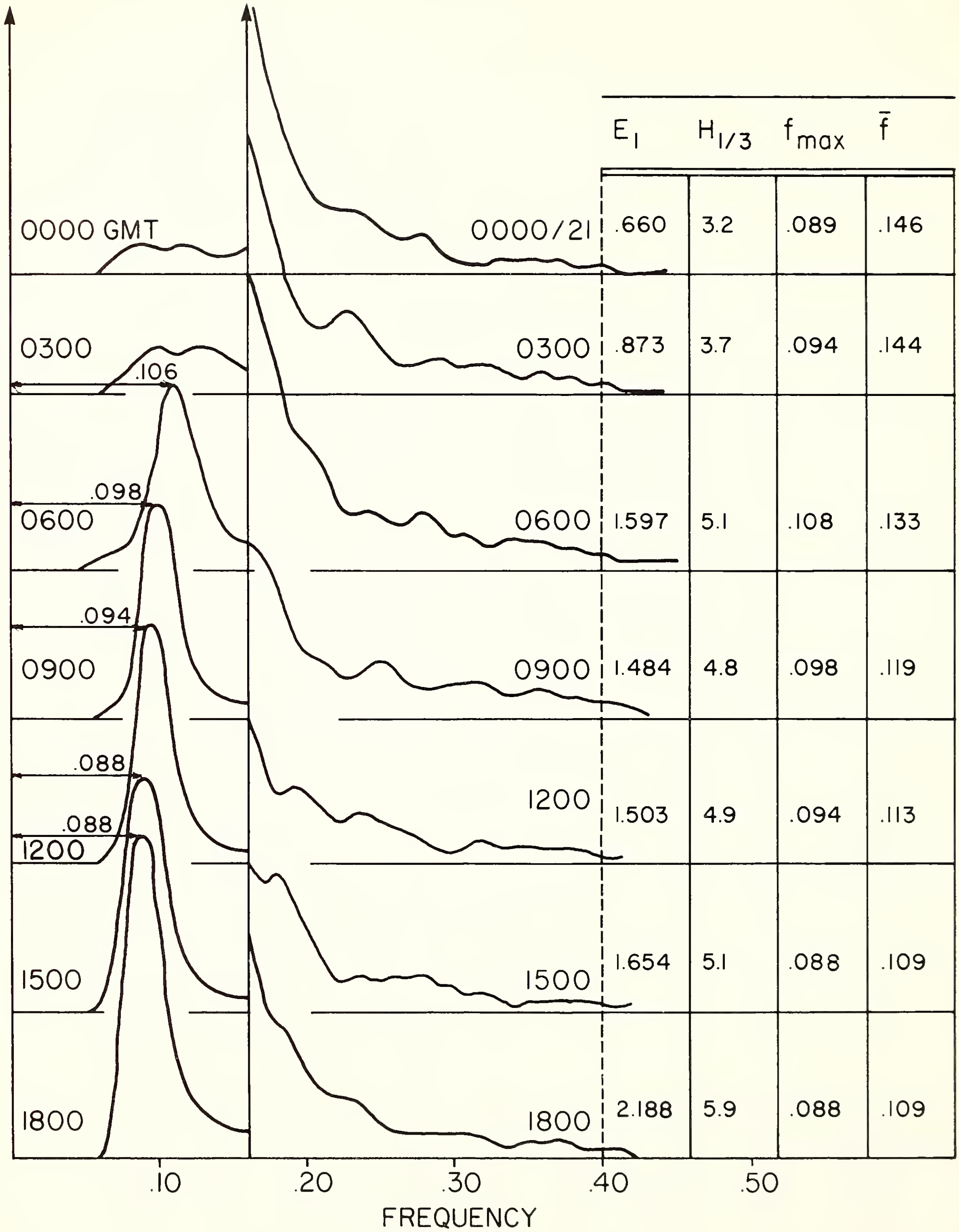
EB03 SPECTRAL DATA FOR 21 FEBRUARY 1975

Freq.	0000	0300	0600	0900	1200	1500	1800	2100 (GMT)
01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
04	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
05	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.3
06	1.8	1.3	2.3	1.0	1.3	1.9	0.0	1.0
07	3.8	3.1	3.0	2.3	4.3	14.3	13.7	11.3
08	5.0	5.2	5.1	11.9	17.9	32.6	46.2	33.5
09	5.1	8.6	11.8	32.7	40.4	40.7	54.4	36.6
10	4.5	8.4	25.6	35.5	35.4	27.7	36.8	22.0
11	5.0	7.5	30.9	20.0	15.1	11.7	19.0	10.3
12	4.9	8.1	22.7	9.6	7.9	6.4	9.6	5.5
13	3.5	7.9	13.3	5.8	5.7	4.9	5.9	4.5
14	3.5	7.1	7.4	3.9	2.9	3.7	5.0	3.3
15	4.5	5.5	5.2	3.2	2.3	3.2	4.9	2.4
16	4.7	4.2	4.9	3.0	2.4	2.5	4.0	2.9
17	3.6	3.2	3.9	2.7	1.8	2.2	2.7	2.7
18	2.4	2.0	2.9	1.9	1.2	2.3	2.2	2.0
19	1.7	1.4	2.2	1.2	1.3	1.9	2.0	1.7
20	1.3	1.2	2.0	1.0	1.2	1.3	1.4	1.5
21	1.1	1.1	1.6	0.9	0.9	0.8	1.1	1.2
22	1.1	1.3	1.0	0.7	0.7	0.5	1.0	1.1
23	1.1	1.4	0.9	0.7	0.9	0.6	1.0	1.4
24	0.9	1.1	1.0	0.9	0.9	0.6	0.8	1.4
25	0.7	0.7	0.9	1.0	0.7	0.5	0.6	0.9
26	0.6	0.5	0.8	0.8	0.6	0.6	0.5	0.7
27	0.7	0.5	1.0	0.5	0.5	0.6	0.5	0.6
28	0.7	0.6	1.0	0.5	0.4	0.6	0.5	0.5
29	0.4	0.6	0.8	0.5	0.2	0.5	0.5	0.5
30	0.2	0.5	0.6	0.6	0.2	0.4	0.5	0.5
31	0.2	0.5	0.6	0.6	0.3	0.3	0.5	0.5
32	0.2	0.5	0.4	0.6	0.4	0.3	0.4	0.5
33	0.3	0.4	0.5	0.4	0.3	0.2	0.3	0.6
34	0.3	0.3	0.5	0.4	0.3	0.1	0.2	0.7
35	0.3	0.3	0.5	0.5	0.3	0.2	0.3	0.7
36	0.3	0.4	0.4	0.5	0.3	0.2	0.3	0.5
37	0.3	0.3	0.4	0.4	0.3	0.2	0.4	0.4
38	0.2	0.3	0.3	0.4	0.3	0.2	0.3	0.3
39	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.3
40	0.2	0.2	0.2	0.3	0.1	0.1	0.2	0.3
41	0.1	0.1	0.2	0.3	0.1	0.1	0.2	0.2
42	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2
43	0.0	0.1	0.2	0.1	0.1	0.1	0.1	0.2
44	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1
45	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
46	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
47	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1
48	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.1
49	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1
50	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1
E_1	.661	.872	1.597	1.485	1.508	1.656	2.188	1.564
$4\sqrt{E_1} = H_{1/3}$ (m)	3.23	3.7	5.1	4.9	4.9	5.1	5.9	5.0
$H_{1/3}$ (ft)	10.8	12.1	16.7	16.1	16.1	16.7	19.4	16.4
f_{max}	.09	.09	.11	.10	.09	.09	.09	.09
$\bar{f}$	.150	.145	.134	.124	.115	.109	.110	.119
T_p	11.2	10.6	9.3	10.2	10.6	11.4	11.4	11.4
L_o (ft)	642	575	443	533	575	665	665	665
$H_{1/3}/L_o$	1:59	1:43	1:27	1:33	1:36	1:40	1:34	1:41

TABLE 14

EB03 SPECTRAL DATA FOR 22 FEBRUARY 1975

Freq.	0000	0300	0600	0900	1200	1500	1800	2100 (GMT)
01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
04	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
05	1.0	1.3	3.4	7.6	7.7	3.1	0.1	0.0
06	2.0	3.6	6.3	18.4	34.1	17.1	13.1	4.0
07	10.6	12.4	21.2	38.1	43.0	46.4	36.0	17.3
08	26.0	23.8	39.0	67.1	30.5	59.0	45.0	28.6
09	30.2	23.9	38.2	60.8	22.0	39.4	30.1	26.4
10	22.6	15.8	26.9	31.8	19.5	18.5	16.7	17.8
11	13.2	9.1	20.1	19.7	13.5	10.6	12.9	12.6
12	9.8	7.0	13.7	19.6	9.1	8.2	9.3	9.1
13	8.5	6.8	6.6	15.0	8.3	8.0	6.9	5.7
14	6.0	5.1	3.8	8.4	6.3	7.9	6.0	4.2
15	3.8	3.9	4.1	5.4	4.1	6.2	4.6	3.7
16	2.3	3.4	3.7	4.2	4.0	4.4	3.0	3.0
17	1.6	2.5	2.5	2.9	3.8	2.9	1.9	2.3
18	1.2	1.8	1.7	2.1	2.8	1.7	1.5	1.5
19	1.3	1.3	1.6	1.8	2.0	1.2	1.3	0.8
20	1.5	1.0	1.4	1.2	1.6	1.4	1.2	0.6
21	1.4	1.0	1.1	1.0	1.5	1.5	1.4	0.8
22	1.0	0.9	1.0	1.0	1.5	1.4	1.3	0.9
23	0.7	0.8	0.8	0.9	1.4	1.2	0.9	0.6
24	0.7	0.6	0.7	0.8	1.2	0.8	0.7	0.4
25	0.6	0.4	0.5	0.7	0.9	0.7	0.7	0.4
26	0.5	0.4	0.3	0.6	0.8	0.6	0.4	0.4
27	0.6	0.4	0.3	0.6	0.7	0.4	0.4	0.5
28	0.6	0.3	0.2	0.6	0.7	0.3	0.5	0.4
29	0.6	0.3	0.3	0.6	0.6	0.5	0.4	0.3
30	0.5	0.2	0.3	0.5	0.5	0.4	0.2	0.3
31	0.4	0.2	0.2	0.5	0.5	0.2	0.2	0.3
32	0.4	0.2	0.2	0.5	0.6	0.2	0.2	0.3
33	0.3	0.2	0.2	0.3	0.5	0.2	0.2	0.3
34	0.3	0.2	0.1	0.2	0.5	0.3	0.2	0.2
35	0.4	0.1	0.1	0.2	0.6	0.4	0.2	0.2
36	0.4	0.1	0.2	0.3	0.6	0.5	0.2	0.2
37	0.2	0.1	0.2	0.3	0.6	0.4	0.2	0.2
38	0.2	0.1	0.2	0.2	0.6	0.2	0.2	0.2
39	0.2	0.2	0.1	0.2	0.5	0.2	0.2	0.1
40	0.2	0.1	0.1	0.2	0.4	0.2	0.1	0.1
41	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1
42	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
43	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
44	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
45	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
46	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
47	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
48	0.1	0.0	0.0	0.1	0.2	0.1	0.0	0.1
49	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.0
50	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0
E_1	1.528	1.303	2.022	3.152	2.290	2.474	1.990	1.454
$4\sqrt{E_1} = H_{1/3}$ (m)	4.9	4.6	5.7	7.1	6.1	6.3	5.6	4.8
$H_{1/3}$ (ft)	16.1	15.1	18.7	23.3	20.0	20.7	18.4	15.7
f_{max}	.09	.09	.08	.08	.07	.08	.08	.08
$\bar{f}$	.116	.113	.106	.101	.107	.101	.103	.110
T_p	11.4	11.6	11.9	12.2	14.5	12.8	12.7	12.0
L_o (ft)	665	689	725	762	1076	839	826	737
$H_{1/3}/L_o$	1:41	1:46	1:39	1:33	1:54	1:41	1:45	1:47



	E_1	$H_{1/3}$	f_{max}	$\bar{f}$
0000/21	.660	3.2	.089	.146
0300	.873	3.7	.094	.144
0600	1.597	5.1	.108	.133
0900	1.484	4.8	.098	.119
1200	1.503	4.9	.094	.113
1500	1.654	5.1	.088	.109
1800	2.188	5.9	.088	.109

Figure 42 - Spectral data, EB03, 21 February 1975.

little to 955 millibars. The wind at the buoy is still from east-southeast, but has increased from 19 to 26 knots, the highest speed recorded throughout the day. Some swell is now clearly evident in the spectral graph, and the significant wave height has increased from 3.7 meters to 5.1 meters. The peak frequency is 0.106, corresponding to a period of 9.4 seconds. At this stage the waves at the buoy were probably fairly steep.

The subsequent behavior of the spectral diagrams for 0900, 1200, and 1500 GMT provides a strong clue as to the movement and development of the depression, something which is not provided by the ship reports on the synoptic charts. Although the peak frequency falls successively to .098, .094 and .088, with corresponding increasing periods of 10.2, 10.6 and 11.4 seconds, the significant wave height does not increase rapidly as might be expected. At 0900 GMT the significant wave height falls from 5.1 to 4.8, although later in the day it increases once more to attain a maximum value of 5.9 meters at 1800 GMT.

It is not a difficult matter to reconcile these facts with the movement of the depression. Since the significant wave height and the wind velocity did not increase, it must have slowed down on entering the Gulf and turned northward.

The 1800 GMT chart for 21 February shows that EB03 is still experiencing a southerly or southeasterly air stream. However, cold air is beginning to be entrained off the cold Alaskan hinterland as the center crossed the coast in the region of Anchorage.

The synoptic charts for 22 February (see Chapter 15) confirm this and show that two separate centers develop.

Although the actual situation may now have become a little complex, the main features are not in doubt. Cold air masses associated with arctic fronts progressed southeastwards toward EB03 and, as expected, the sea and swell developed further once the fronts arrived at the buoy on 22 February. An examination of Table 13, which lists the spectral data for that day, shows that the greatest significant wave height recorded was 7.1 meters at 0900 GMT. The greatest peak frequency was about 0.69 at 1200 GMT, corresponding to a period of 14.5 seconds.

The synoptic situation discussed above was a little complex, and the synoptic analyses were subjective as a result of lack of data over the sea areas; but an able forecaster could use the sequence behavior of the significant wave heights and periods at the buoy to deduce the synoptic developments that were actually taking place.

12.3 Environmental factors and wave generation at EB03 and PAPA. It is of some interest that the maximum significant wave height was 7.1 meters at the buoy and only 4.9 meters at Ocean Weather Station PAPA (see

TABLE 15

WAVE PARAMETERS DERIVED FROM SPECTRAL DATA AT OCEAN STATION PAPA FOR 21-22 FEBRUARY 1975

	GMT/Date											
	0230	0530	0830	1130	1430	1730	2030	2330	0230	0530	0830	1130
	21								22			
†E	17.6	16.6	21.1	20.5	9.5	16.0	14.3	18.2	30.0	29.9	32.2	28.6
*E_1	0.83	0.78	0.99	0.96	0.45	0.75	0.67	0.86	1.41	1.40	1.51	1.34
†$H_{1/3}$	11.9	11.5	13.0	12.8	8.7	11.3	10.7	12.1	15.5	15.5	16.1	15.1
*$H_{1/3}$	3.6	3.5	4.0	3.9	2.7	3.5	3.3	3.7	4.7	4.7	4.9	4.6
T_p	13.7	10.5	10.5	9.8	11.4	10.5	12.4	11.4	13.7	12.4	10.5	11.4
†L_o	961	564	564	492	665	564	787	665	961	787	564	665
$H_{1/3}/L_o$	1:81	1:49	1:43	1:38	1:75	1:49	1:73	1:55	1:63	1:51	1:35	1:44

†English units
*metric units

Table 15). Note also that the waves were consistently steeper at the buoy than at PAPA. The fetch was much greater at PAPA, and, if anything, wind speeds were higher. But this was more than offset by the bite of the air masses and by the comparatively rapid reversal of the wind direction at the buoy. Note that there was a considerable drop in temperature at EB03 after 0300 GMT on 22 February and that the highest significant waves developed after this. If we look at the dew point temperatures, we see that they dropped at both locations and that the highest seas occurred after the cold air arrived.

The important elements in sea and swell generation for the two -day period are listed in Table 16, and it is readily seen that although the wind speeds are consistently higher at Ocean Station PAPA than at EB03, the significant wave heights are in almost all cases higher at the buoy. This perhaps is largely due to a recognized tendency of the anemometers on the buoys to under-record wind speeds. Nevertheless, the values of $\varrho a - \varrho s$ at the buoy are almost double those at PAPA once the cold mass has arrived at the respective positions.

TABLE 16

COMPARATIVE VALUES OF IMPORTANT ENVIRONMENTAL FACTORS AT EB03 AND OCEAN STATION PAPA FOR 21-22 FEBRUARY 1975

GMT/Date	Wind Speed (kn)		Sea Temp. (°C)		Air Temp. (°C)		Dew Point (°C)		Surface Pressure (mb)		$\varrho a - \varrho s$ (kg/m^3)	
	EB03	PAPA	EB03	PAPA	EB03	PAPA	EB03	PAPA	EB03	PAPA	EB03	PAPA
00/21	19	29	3.3	5.4	2.6	6.7	1.9	6.2	987	984	+.000	−.007
03	23	30	3.3	5.1	2.5	6.6	1.8	6.2	978	981	+.001	−.007
06	26	24	3.3	5.4	2.1	6.8	1.6	6.6	970	981	+.003	−.007
09	14	17	3.3	5.5	2.8	6.5	2.3	6.0	967	982	+.010	−.006
12	12	19	3.3	5.4	3.5	6.4	2.8	5.9	968	981	−.004	−.005
15	13	15	3.3	5.4	3.4	6.7	2.4	5.8	968	980	−.002	−.005
18	14	15	3.3	5.4	3.6	4.7	1.0	4.2	968	981	−.002	+.004
21	16	32	3.3	5.4	3.5	5.3	1.7	4.4	968	983	−.002	+.001
00/22	08	29	3.3	5.5	2.8	6.1	2.2	2.0	969	987	+.004	−.001
03	14	25	3.3	5.1	2.0	3.9	−1.3	2.2	971	993	+.005	+.006
06	10	19	3.3	5.1	0.2	4.5	−3.0	−0.1	975	997	+.013	+.004
09	13	11	3.3	5.3	0.0	4.3	−6.8	−0.4	982	998	+.016	+.007

12.4 The establishment of statistical relationships between significant wave height and meteorological elements. Figure 43 shows plots of significant wave height measured every three hours at EB03 together with corresponding graphs of wind speed, temperature, and dew point for a 12-day period from 16 to 28 February 1975.

To test these apparent relationships, series of regular observations of significant wave heights were correlated with wind speed and temperature values. Three hourly data from Ocean Station PAPA and EBO3 were used. In each test, at least 100 consecutive observations were taken, which corresponds roughly to approximately two weeks of data. Table 17 shows the results of correlating significant wave heights with wind speeds from PAPA using zero stagger, zero minus three hours, zero minus six hours, zero minus nine hours, and zero minus twelve hours, and, in addition, correlating with a mean wind speed value of $(U_O + 2U_{-3} + U_{-6})/4$, since this appeared to give on all data tested larger correlation coefficients. The results indicate that the highest seas are obtained some four and a half hours after the wind reaches its maximum value, a time lag which is not unreasonable. Three independent time series were used in this test as follows:

(a) Ocean Station PAPA from 18-31 January 1975.
(b) Ocean Station PAPA from 31 January to 15 February 1975.
(c) Ocean Station PAPA from 15 February to 28 February 1975.

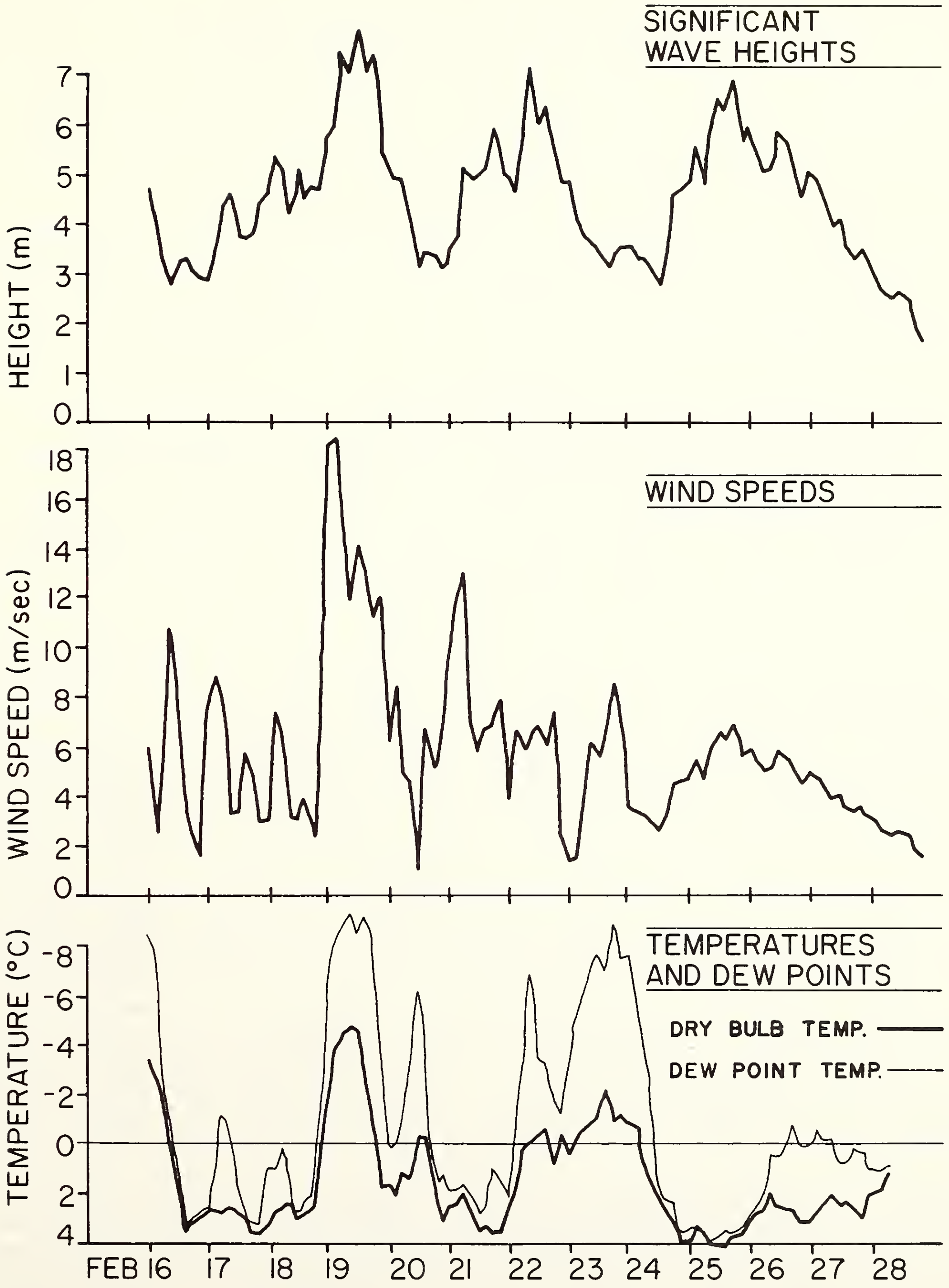


Figure 43 - Plot of significant wave height at EBO3 with wind speed, temperature, and dew point for 16-28 February 1975.

TABLE 17

CORRELATION COEFFICIENTS BETWEEN SIGNIFICANT WAVE HEIGHTS AT STAGGERED INTERVALS OF 3 HOURS AT OCEAN STATION PAPA

Series	U_0	U_{-3}	U_{-6}	U_{-9}	U_{-12}	$(U_0 + 2U_{-3} + U_{-6})/4$
(a)	.69	.72	.72	.65	.55	.78
(b)	.72	.74	.72	.65	.60	.76
(c)	.45	.50	.46	.37	.19	.55
Mean	.62	.65	.63	.56	.45	.70

TABLE 18

CORRELATION COEFFICIENTS BETWEEN SIGNIFICANT WAVE HEIGHTS AT STAGGERED INTERVALS OF 3 HOURS AT EBO3

Series	U_0	U_{-3}	U_{-6}	U_{-9}	U_{-12}	$(U_0 + 2U_{-3} + U_{-6})/4$
(d)	.46	.51	.44	.36	.23	.55
(e)	.50	.61	.65	.56	.52	.70

A similar study was carried out using EBO3 data for two periods: (d)4 December 1974 to 11 January 1975 (5½ weeks); (e) from 16-28 February 1975. The results are given in Table 18.

For 100 pairs of values, the correlation coefficients at the significant levels of 5% and 1% are 0.197 and 0.256, respectively. Tables 17 and 18 all have correlation coefficients above the 1% significance level except at U minus 12 hours. This implies that in less than one case out of a hundred that the observations will not be correlated. The correlation coefficients are high because the major cause of wave development is the wind.

In each of these five independent studies, the trend is the same. More studies of this type are desirable from all buoy positions and weather ship stations for various times of the year. To date, a three-month period only for the midwinter of 1975 has been studied, but the results of these analyses strongly suggest that it should be possible to produce simple empirical rules to give quick results to the forecaster. For example, suppose a forecast of significant wave height is required at a specific location for twelve hours ahead. The forecaster would first need to derive from his synoptic charts sequences the forecast wind values at the point for six, nine, and twelve hours ahead and from these calculate a mean wind speed of $(U_6 + 2U_9 + U_{12})/4$. Subsequent reference to a graph would give him a significant wave height of considerable accuracy for the time required. This is in conformity with the view of seamen that if only the winds can be forecast accurately, they have a very good idea of what the sea will do. A seasonal approach along these lines might well give better results.

In amplification of this remark, all significant wave heights of Ocean Station PAPA were abstracted during the three-month winter period when the wind speed fell below fifteen knots. The average value derived from 56 such readings was a significant wave height of 3.15 meters. Using significant wave heights for three hours later (during which time the seas were presumably decreasing), reduced the average value to 3.08 meters. When the stagger was six hours, the average was only 3.00 meters after which the values increased once more. This suggests that in winter, approximately 3.0 meters of sea and swell are always present at Ocean Station PAPA and that a fairly reliable forecast can be obtained by adding to it the amount which would be derived from sea generated by the local wind.

A provisional examination of certain similar summer data at EBO3 indicated that the average residual swell when winds were less than 13 knots is 1.75 meters in June and probably less in July and August.

Similar correlation studies are also necessary between significant wave heights and air temperature, sea surface temperature and dew point. Some figures are given in Table 19, but are provisional figures only derived from data from Ocean Station PAPA for two short periods: (a) 18-31 January 1975; (b) 16-28 February 1975.

TABLE 19

CORRELATION COEFFICIENTS BETWEEN SIGNIFICANT WAVE HEIGHTS AND VARIOUS FACTORS INVOLVING WIND AND TEMPERATURE AT OCEAN STATION PAPA

Series	Parameter	0	-3 hours	-6 hours	-9 hours	-12 hours
(a)	U	.69	.72	.72	.65	.55
	U^2	.67	.71	.71	.66	.52
	$(1/T_a - 1/T_s)$	.48	.38	.29	.19	.09
	U/T_a	.67	.70	.67	.62	.51
	$1/T_a$	.61	.50	.38	.23	.10
Series (b)	U	.45	.50	.46	.37	.19
	U/T_a	.47	.50	.45	.37	.26

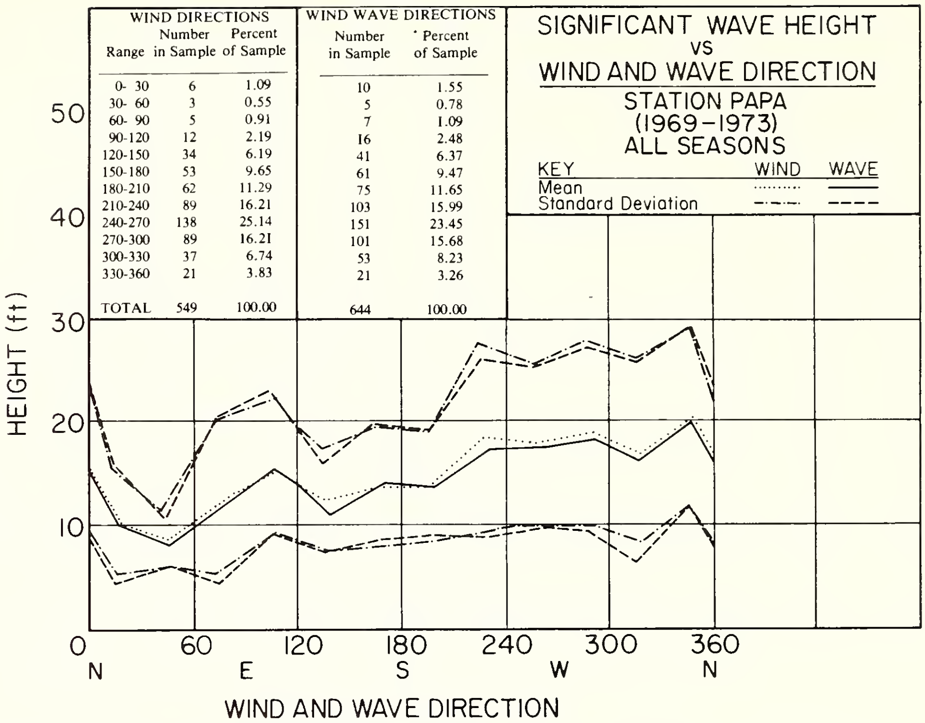
It would be desirable to deduce simple formulas in which Significant Wave Height = $A + B\,U_f + C/T_f$ where A, B, and C are constants, U_f is a forecast wind speed, and T_f is a forecast temperature factor which reflects air density.

It is suggested that such formulas could be developed for all buoy positions and for Ocean Station PAPA on a seasonal basis and have further application for all point forecasting to obtain a quick answer for either a forecaster or the master of a ship. Some adjustment to the answer could be made for the effects of major frontal zones or for swell from a distant storm.

12.5 Statistical analysis of sequences at Ocean Weather Station INDIA and Ocean Station PAPA. The following diagrams are instructive and have been abstracted from the report by the Webb Institute of Naval Architecture, *Analysis of Wave Spectra at Station PAPA,* by D. Hoffman as a portion of the SEA USE Foundation final report on Directional Wave Spectral Investigations in the North Pacific to the U.S. Maritime Administration.

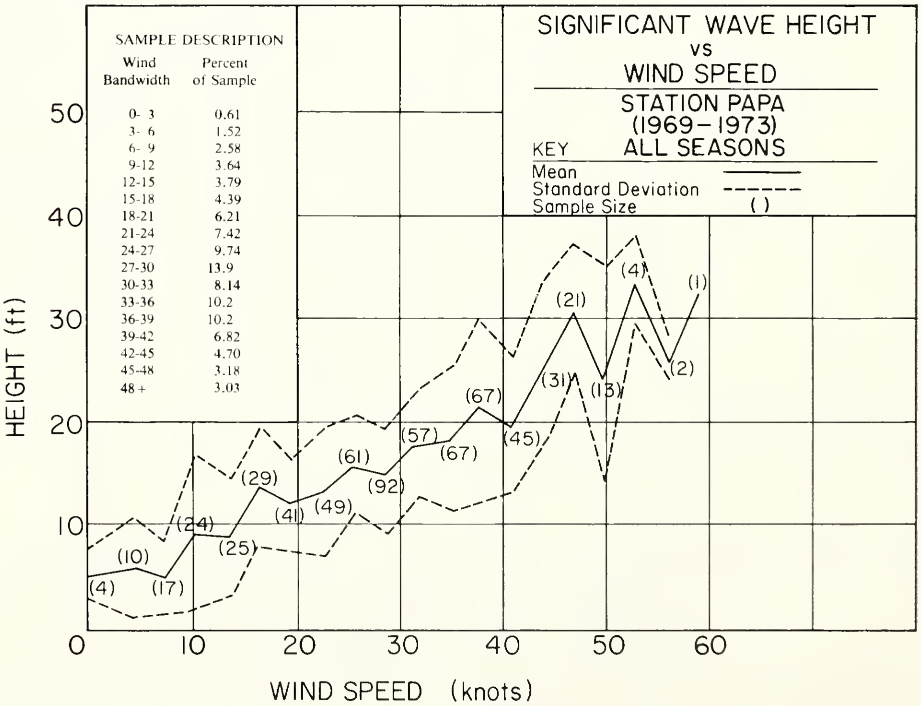
Figure 44 represents a plot of the significant wave heights corresponding to various wind and wave directions at Ocean Station PAPA. Insufficient numbers of observations are available to reach firm conclusions, but it is of interest to note that the maximum heights do not occur with winds from the prevailing wind direction where there is the longest fetch and the maximum prospect of duration. The greatest heights occur with winds between west and north where the fetch is more limited but the air masses contain a higher proportion of cold fronts.

Figure 45 represents a plot of significant wave heights against wind speeds at PAPA for all seasons of the year. It is seen that the relationship is approximately a linear one, although few observations were available for wind speeds in excess of 50 knots. The graph approximates closely to the one given in Britton's graph (derived mainly from buoy data) shown in Figure 26, Chapter 7 applicable to average circumstances. The mean line through the plots does not pass through the origin. This is because the analyses dealt at all times with spectra concerning a combination of sea and swell. At wind speeds less than 10 knots and particularly in calms when the wind speed may be recorded at zero, some swell is always present in the open ocean; hence, some wave



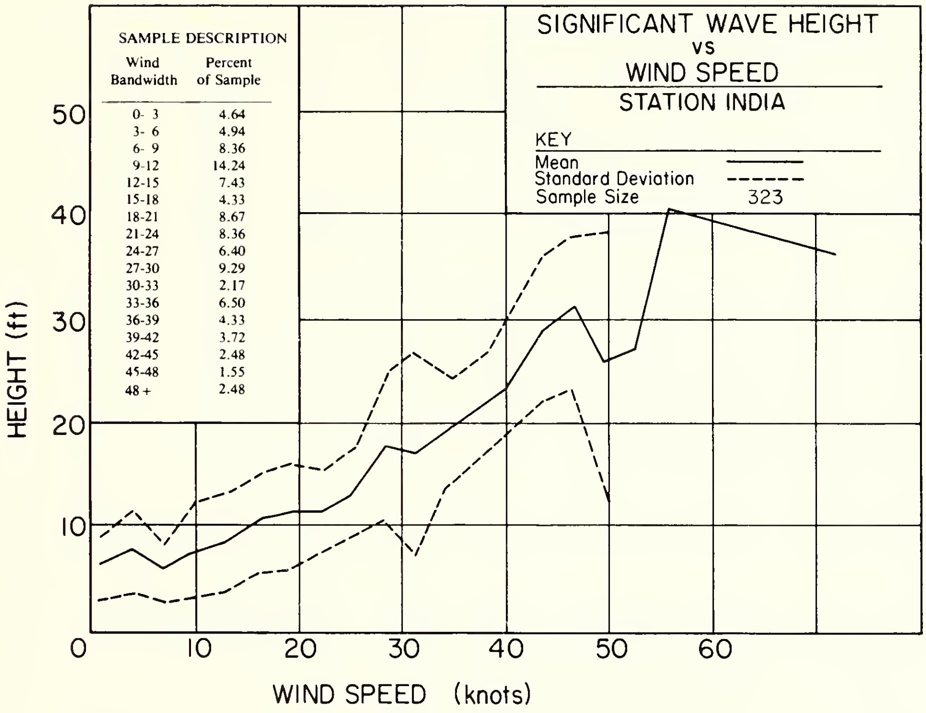
WIND DIRECTIONS Range	Number in Sample	Percent of Sample	WIND WAVE DIRECTIONS Number in Sample	Percent of Sample
0- 30	6	1.09	10	1.55
30- 60	3	0.55	5	0.78
60- 90	5	0.91	7	1.09
90-120	12	2.19	16	2.48
120-150	34	6.19	41	6.37
150-180	53	9.65	61	9.47
180-210	62	11.29	75	11.65
210-240	89	16.21	103	15.99
240-270	138	25.14	151	23.45
270-300	89	16.21	101	15.68
300-330	37	6.74	53	8.23
330-360	21	3.83	21	3.26
TOTAL	549	100.00	644	100.00

Figure 44 - Significant wave height versus wind and wave direction at Station PAPA (1969-1973).



Wind Bandwidth	Percent of Sample
0- 3	0.61
3- 6	1.52
6- 9	2.58
9-12	3.64
12-15	3.79
15-18	4.39
18-21	6.21
21-24	7.42
24-27	9.74
27-30	13.9
30-33	8.14
33-36	10.2
36-39	10.2
39-42	6.82
42-45	4.70
45-48	3.18
48 +	3.03

Figure 45 - Significant wave height versus wind speed at Station PAPA (1969-1973).



SAMPLE DESCRIPTION

Wind Bandwidth	Percent of Sample
0- 3	4.64
3- 6	4.94
6- 9	8.36
9-12	14.24
12-15	7.43
15-18	4.33
18-21	8.67
21-24	8.36
24-27	6.40
27-30	9.29
30-33	2.17
33-36	6.50
36-39	4.33
39-42	3.72
42-45	2.48
45-48	1.55
48 +	2.48

Figure 46 - Significant wave height versus wind speed at Station INDIA.

height will normally be recorded, measured, or estimated. The standard deviations at the various wind speeds are shown as dotted lines and are sufficiently large to be in accord with previous statements that the relationship between significant wave heights and wind speeds varies with air mass/sea surface temperature characteristics. Nevertheless, use of such an approximate straight line relationship is obviously a valuable aid in practical forecasting.

Figure 46 represents the similar graph for data from Ocean Weather Station INDIA.

Figures 47 and 48 represent plots of measured significant wave heights at Ocean Stations PAPA and INDIA against the observed wave heights made by experienced observers on board the vessels. It provides good evidence that trained observers make estimates which approximate closely to the top third of the waves in the spectra. The agreement is surprisingly close in view of the fact that estimates made of wave heights at night are very difficult and liable to considerable error. The figure also lends support to the view that observers tend to underestimate the height of waves at low wind speeds.

For example, in Figure 47, we can see that a measured significant wave height of five feet was estimated by eye to be only two feet. At a measured height of 20 feet, the estimated height was about 18 feet. The height of the observer above the water plays an important part in estimating wave heights, especially when the waves are small and the observer is aboard a large ship. If the manual observation agreed exactly with the measured heights, the graph, of course, would be the straight line shown in figure 47.

Figure 49 represents a plot of significant wave heights at PAPA against the average wave period in seconds. Almost all the observations were contained in the range from five to eleven seconds, and it would be unwise to use the graph for practical purposes outside this range of values. Within the range the relationship is approximately linear, although the standard deviations of range for any particular period are relatively high. Nevertheless, the first stage in forecasting is to produce a time wind field at surface level and then forecast the significant wave height by an empirical method. The problem then facing a forecaster is often to deduce from this the

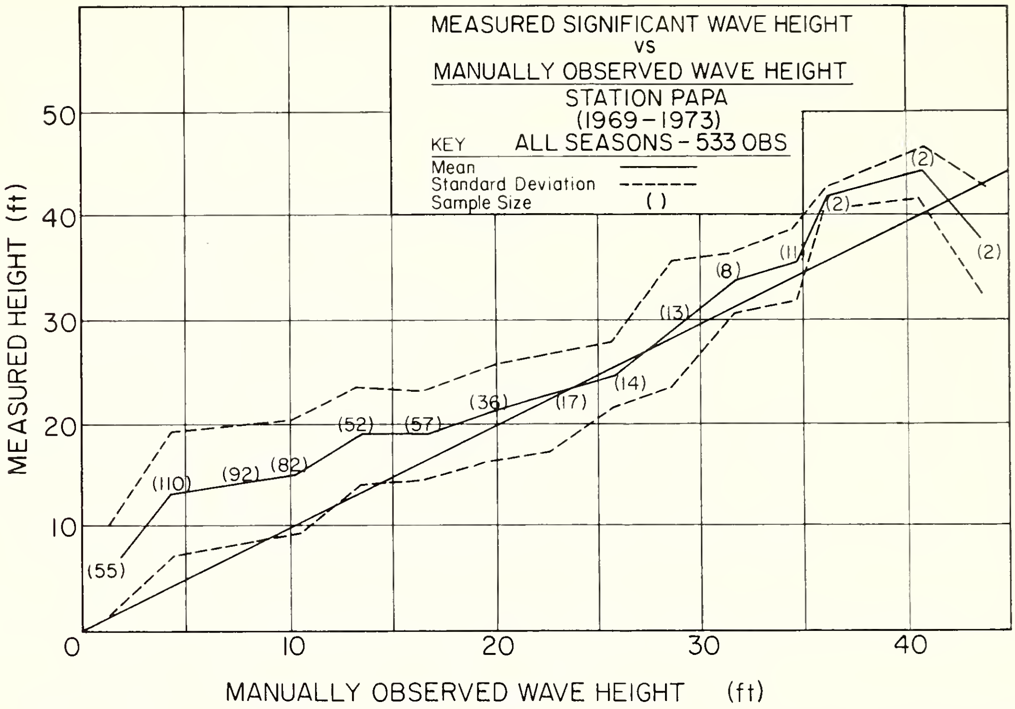


Figure 47 - Measured significant wave height versus observed wave height at Station PAPA (1969-1973).

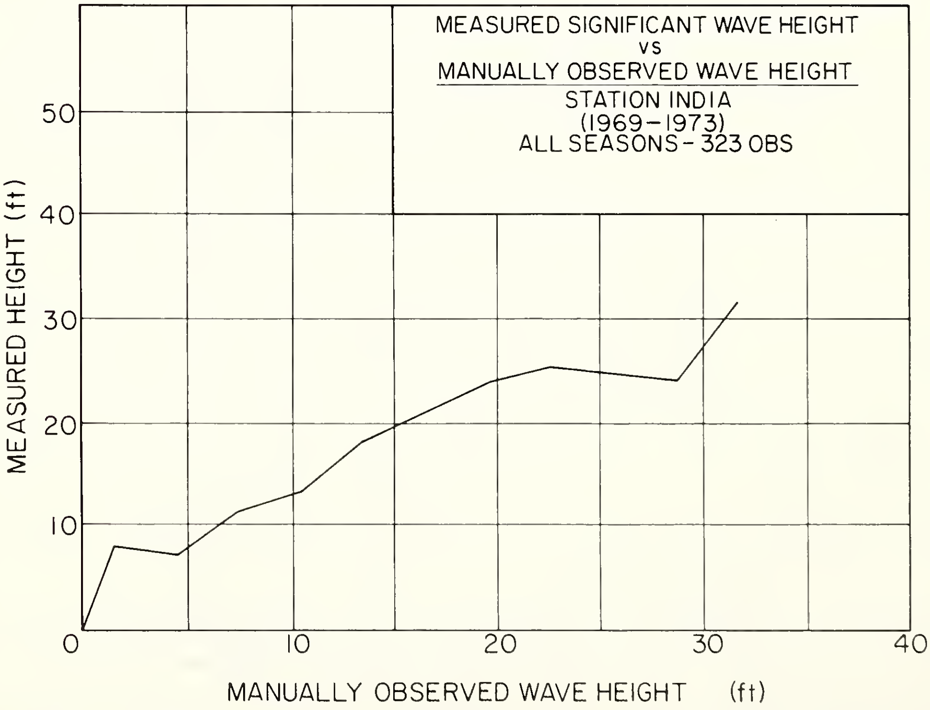
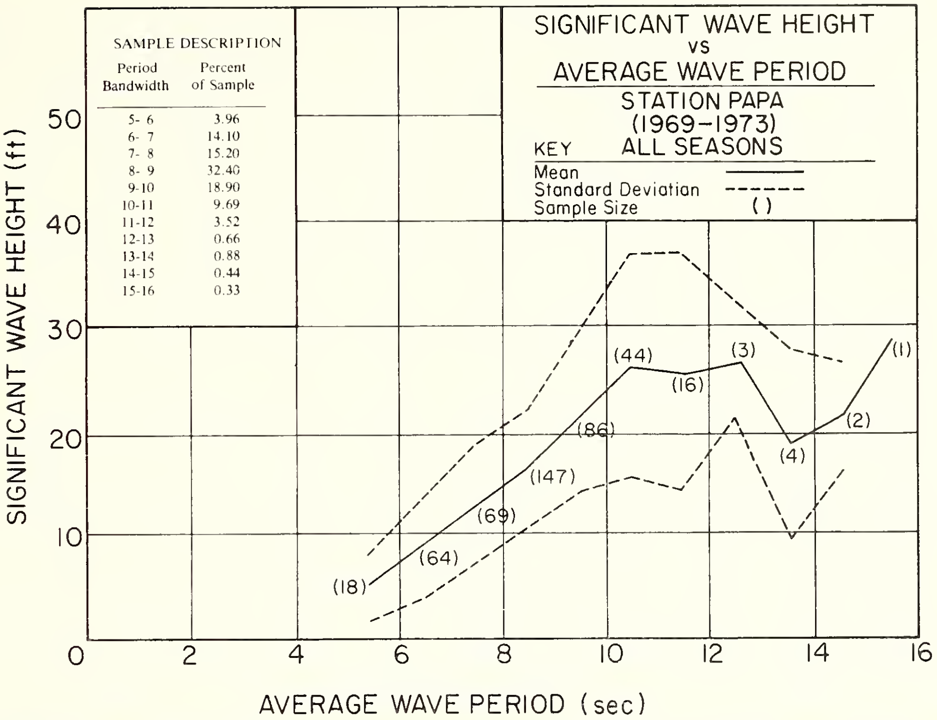


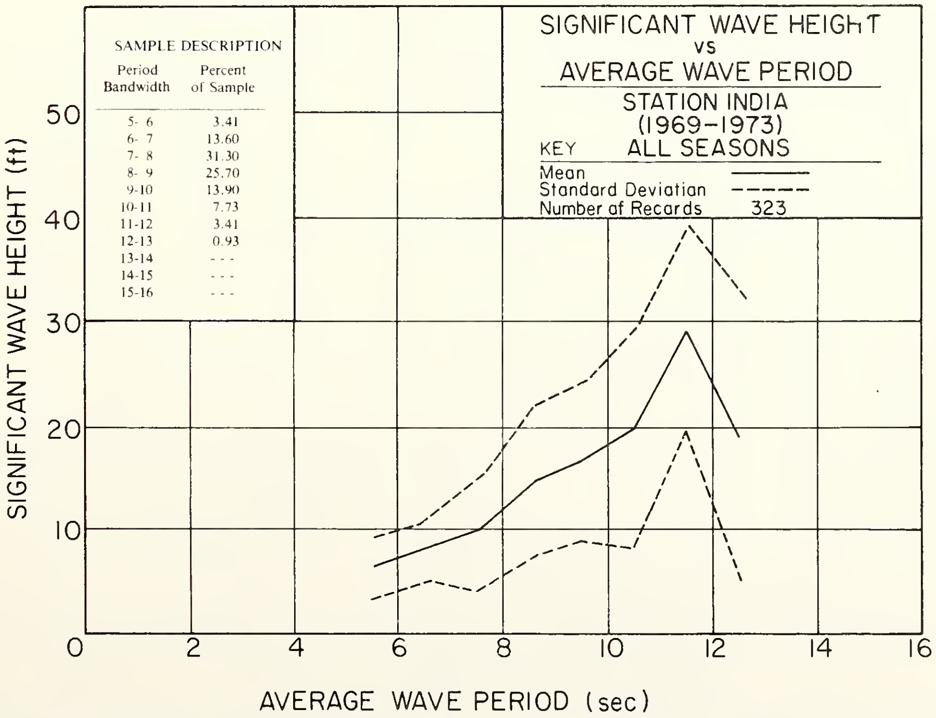
Figure 48 - Significant wave height versus observed wave height at Station INDIA (1969-1973).



SAMPLE DESCRIPTION

Period Bandwidth	Percent of Sample
5- 6	3.96
6- 7	14.10
7- 8	15.20
8- 9	32.40
9-10	18.90
10-11	9.69
11-12	3.52
12-13	0.66
13-14	0.88
14-15	0.44
15-16	0.33

Figure 49 - Significant wave height versus average wave period at Station PAPA (1969-1973).



SAMPLE DESCRIPTION

Period Bandwidth	Percent of Sample
5- 6	3.41
6- 7	13.60
7- 8	31.30
8- 9	25.70
9-10	13.90
10-11	7.73
11-12	3.41
12-13	0.93
13-14	- - -
14-15	- - -
15-16	- - -

Figure 50 - Significant wave height versus average wave period at Station INDIA (1969-1973).

corresponding wave period. Figure 49 is an obvious aid to this process.

Figure 50 shows the corresponding graph of significant wave height against average wave period derived from the data from Ocean Weather Station INDIA. The agreement is again close, but shows that the approximate straight line relationship should only be used in the band from five to eleven seconds. The simple reason is that the spectral analyses from which the graphs are derived do not seek to distinguish sea from swell. When the period exceeds five seconds, we may be concerned with seas that are developing into swells, and it is clearly impossible to say when this happens precisely.

CHAPTER

13

THE EFFECT OF FRONTS ON SEA AND SWELL GENERATION

13.1 Introduction. In the simplest terms, a front may be defined as the boundary line between two air masses of different origin. In consequence, unless the air masses have been modified considerably on passage from the area of origin, they have different temperature and humidity content and, hence, different densities. When a change takes place there will usually be discontinuities in several environmental parameters and in particular the wind speed and direction; these factors will influence the sea state. Sometimes, when the density difference is small, the change from one air mass to the other is gradual, and the discontinuities in wind speed and direction, temperature, humidity, visibility, and so forth are difficult to identify and do not occur simultaneously. Hence, meteorologists often prefer to speak of frontal zones as opposed to frontal lines since this enables them to introduce some latitude when timing the arrival of changes at a specific location.

However, there will be occasions when the discontinuity is sharp; the frontal passage is sudden and accompanied by violent squalls. In line squalls, the effects may only last for a few minutes, but this is quite sufficient to cause problems to small craft, particularly to those under sail. In contrast, frontal passages in major depression systems may cause confused seas for an hour or two. The swell generated in an air mass in the rear of the advancing front can move faster than the front inself and thereby create cross-seas in its forward path. The situation may be further complicated by any additional cross swell from a distant storm.

13.2 Classification of fronts. The classification of fronts is a complex subject and detail is beyond this book. It is assumed that you have some knowledge of the fundamental differences between warm, cold, and occluded fronts as a result of wave developments on the polar front. Refer to any good textbook on general meteorology if further distinction is required between cold occlusions, cold fronts, polar fronts, and arctic fronts.

The particular interest here lies in the effect of frontal passages on sea and swell generation which largely concerns the effect of discontinuities at surface level; however, the influence of rainfall on the generation of seas will receive special comment. In subsequent chapters, special consideration will be given to the progress of cold fronts (defined as the leading edges of cold air masses) over the ocean surface from arctic regions to the tropics. On passage, the air mass is being continuously modified and, periodically, the frontal surface needs reclassification. In general, arctic fronts are peculiar to arctic regions and are shallow features characterized by almost complete lack of humidity content in both air masses. Hence, there is an almost complete absence of cloud, and severity is generally limited since little or no release of latent heat energy occurs. However, there is a density discontinuity and a wind shift and it may occasion a blizzard from drifting snow. When such dense cold air masses flow off ice shelves or down mountain valleys as katabatic wind out over a warm sea, a very active front develops, and some may contend that it should immediately be classified as "a polar front," though it should not be confused with "the polar front" or necessarily a front associated with a polar low. Such fronts, whether they be called arctic or polar, are often quite difficult to detect, particularly on satellite pictures. The analyst must rely on reports of pressure, temperature, and dew point.

In Chapter 14, cold air outbreaks from the ice shelf in the Weddell Sea in Antarctica will be described along with similar outbreaks from the ice shelf in the Bering Sea and from the southern shores of Alaska in winter. In the initial stages, the leading edge of the cold air mass is probably a true antarctic (or arctic) front. For example, in the antarctic region, as such fronts approach the Falkland Islands in South Orkneys some 24 hours later, they should be reclassified as polar fronts, but it will depend on the length of sea passage from the edge of the pack ice and the speed of advance. The subsequent progress of the air mass across the ocean to lower latitudes is often an interrupted one depending on the path taken, and air masses would be sufficiently modified to affect the Argentine or the island of Tristan de Cunha as simple cold fronts. Further progress may then be impeded by the subtropical high pressure cell, particularly at surface level. The progress of the air mass towards the equator at upper levels is often not so restricted. Thus, cold fronts passing across the South American coastline pass Monte de Video in Uraguay with the typical discontinuities of any cold front, but they are first noticeable by the arrival of high clouds at Rio de Janeiro. This has caused some meteorologists to write of the conversion of cold fronts into warm fronts, a concept which some find difficult to entertain.

Those cold fronts, and they are the majority, which take a more easterly passage past the island of Tristan de Cunha finally approach Cape waters where the cold air mass can deviate to the left into the col between two subtropical high pressure cells. The cold front frequently degenerates into a line squall in the trade wind zone. Thus, there has been a steady transition over a period of several days from an antarctic front to a polar front, to a cold front, to a line squall. Just where such changes in type occurred will vary with definition and is not fundamental to the argument. The important concept is to trace the leading edge of the cold air mass as it progresses over the ocean, realizing that we are tracing basically the same discontinuity over thousands of miles.

The angle of slope of a front is dependent of the density difference between the air masses of a front at any given level, the amount of this density difference being some measure of the severity of the discontinuity. Air density was discussed in some detail in Chapter 4 and was shown to be dependent on temperture, pressure, and humidity. One useful measure of an air mass that enables a forecaster to assess a change in the relative severity across it is the wet bulb potential temperature. Generally, this has to be deduced from radiosonde observations and such data are not always available. Wet bulb potential temperature is a conservative quantity, which does not alter with variations of pressure and temperature.

The type of front that particularly affects sea and swell generation is the cold front or cold occlusion since ϱa, the density of the air mass behind the front, is usually more than ϱs, the air density corresponding to the sea surface temperature. The greater $\varrho a - \varrho s$, the greater the effect of the wind on the water surface. Generally, frontal effects which have maximum impact are experienced when values of $(\varrho a_1 - \varrho a_2)$ are large, where ϱa_1 is the density of the air in the rear of the cold front, and ϱa_2 is the density of the air mass ahead of the front.

13.3 The task of the forecaster. Forecasting the sea and swell conditions in the neighborhood of a front is a difficult matter, and the timing is usually only possible with the aid of synoptic charts on which there are a number of surface observations from ships of opportunity, weather ships, and buoys. To achieve accuracy, the more of such observations available, the better. Frontal analyses over the sea often call for additional skill and some experience since ship observations* contain a small percentage of errors (usually less than 5%) due to the number of processes the reports must undergo before they appear on the charts. Also, the movement of ships in rough seas can make reporting difficult, and this leads to errors in ships' positions, pressures, and temperatures, and so forth, which, however small, can upset the correct placing of a front.

Computer analyses of fronts on synoptic charts are seldom better than carefully drawn hand analyses even using the latest fine mesh models. The reasons are perhaps obvious. Ideally, a forecaster should seek to locate discontinuities and place them with an accuracy of perhaps little more than 15 miles along the whole length of the front so as to ensure timing the arrival at a location to within one hour. It is impossible to achieve this

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**Ed. note: Taking atmospheric measurements at sea is often a very difficult process, especially in stormy weather in which temperature measurements can not only be affected by spray, but by the understandable tendency of a person to stay outside as short a time as possible to obtain psychrometric readings. Readings of barometric pressures are affected by wind flow around the ship's superstructure and the calibration of the barometer itself. The editor has observed cases in which shipboard barometers have been in error by more than four mb until recalibrated by the Port Meteorological Officer. Generally, shipboard measurements of temperature and pressure are not of the same accuracy as land station measurements; unfortunately, the number of observations is often very small, too.*

degree of accuracy unless the grid-spacing of observations is of comparable magnitude. Such accuracy is of no great consequence in open ocean areas, but with onshore flow over continental shelves, the timing of fronts may be a crucial factor to small craft in inshore waters. Best results are often only achieved after considering and questioning every scrap of shipping observation available, and this involves first eliminating the more elementary errors in the data by common sense procedures. This may call for reference to consecutive reports from the same ship at the synoptic hours -an effective maneuver which may reveal any errors in position or barometric readings. The correct placement of fronts is aided considerably over the oceans by satellite pictures, which should be fully utilized on all occasions, although high cloud will often obscure what is happening at the surface.

Generally speaking, the better the degree of fit of an analysis to the observations, the greater the chances of making a good sea state forecast. Any ship observation on the chart which is at variance with the final analysis arrived at by the forecaster needs to be checked and investigated manually, and it should never be discarded without considering the possible reasons for the difference and the errors. Unfortunately, shortage of time does not always allow for such investigations to be made routinely in marine weather offices.

The effective wind field charts will normally indicate a maximum of closed isopleths just ahead of a warm front and in the rear of any cold front. With the passage of any front there is usually a veer of wind in the northern hemisphere, and gusty conditions may prevail for some time. The worst sea state conditions are often experienced in the cold air mass in the rear of the low since this air mass is normally colder and denser and can readily impact on the confused seas generated by the preceeding warm front or warm occlusion associated with the low pressure system.

In the rear of a low, particularly after the passage of an arctic front, the development of a cold migratory anticyclone is not an uncommon feature. In these systems it is not unusual for straight isobar situations to occur with some isobars having anticyclonic curvature in which the gradient wind is greater than the geostrophic wind. The length of fetch associated with such situations is often considerable with the resulting potential for raising seas and swells of great magnitude. Gradient winds in a deep depression are often considerabley less than the geostrophic winds, and the closeness of the isobars can mislead an inexperienced forecaster as to the strength of the effective wind at surface level.

A number of wave spectra have recently been obtained from buoys in close proximity to hurricanes in the Gulf of Mexico, and the significant wave heights deduced from such recordings have not always been much higher than 25 feet. Such heights are by no means phenomenal for the open ocean. However, it should be appreciated that hurricanes and typhoons are comparatively localized features and that significant wave heights of 25 feet associated with the confused seas in a confined area are potentially very dangerous to shipping. It is often far more so than significant wave heights of over 35 feet associated with long swells.

13.4 The effects of rainfall. Pouring oil on troubled water has often said to have been a successful maneuver to use, and it is certainly effective in calming the waters if the right type of oil is used in the right quantitities. The oil spreads over the surface of the sea as a thin film, and the surface tension prevents the formation of capillary waves and their growth into gravity waves and seas of any magnitude. The water surface is often rendered glassy in appearance, and the unruffled surface is a clear indication of a lack of transfer of energy from atmosphere to ocean. A "blanket" effect is thus imposed on the "fire." The maneuver would thus appear to be most effective when the evaporation rate is high (*i.e.,* in cold dry air streams), but the important factor is to create a thin film of oil which is periodically replaced. Dumping tons of heavy crude oil onto the sea may have little or no effect and could prove more of a hindrance than an asset.

Rainfall has much the same effect by forming a layer of fresh water over the denser salt water. Since the surface tension of fresh water is greater than that of oil, there is some cause for saying that rainfall is even more effective. The same result is achieved of preventing the formation of capillary waves and their development into large seas. The effect is particularly noticeable in low latitudes during tropical rainstorms, the water surface being rendered glassy in heavy downpours expect for the small puddles created by the impact of the falling droplets. A swell is more readily observed under such circumstances.

Rainfall is seldom mentioned as a factor in sea state decay, but there is little doubt that it exerts some and perhaps a considerable influence. Since rainfall is almost entirely associated over the open ocean with fronts, it is advantageous to consider the present weather reports from shipping observations and make some allowance for rain accordingly, particulary so in depressions which seem to have a number of rainfall observations associated with them.

13.5 Rainfall measurements over the oceans. Good measurements of rainfall over the oceans have defied solution for over a century. To obtain an accurate reading with a rain gauge, siting and mounting are all important. First, the face of the gauge must be horizontal to obtain a true reading, and such level circumstances cannot be achieved on board a moving ship at all times. Also, some turbulent flow of the air around the gauge is unavoidable on account of the superstructure above the water line. In addition, ships have masts with stays that collect droplets; periodically, a proportion of these will finally find their way into the rain gauge. But perhaps the greatest source of error in measurement is the collection of some spray since it cannot be avoided in strong winds. Choppy seas, which cause spray, are often associated with frontal passages, and it is precisely at such times that it is desirable to collect and make measurements.

Some success has been claimed for measurement of rainfall by radar over land, but it is doubtful if any great degree of accuracy can be achieved by this means by ships at sea and certainly not by the average radar set with unstabilized mountings used for navigational purposes and safety. The strength of a return echo from precipitation areas is the basis of the method used on land. It is desirable to eliminate this "interference" as much as possible in a radar used for navigation and detection of other vessels.

13.6 Assessments of rainfall amount and rates at sea. All meteorological observers are taught to assess precipitation according to intensity, and the standard reporting codes allow for such descriptions by delineations such as slight intermittent rainfall, slight continuous, moderate intermittent, moderate continuous, heavy intermittent, and heavy continuous. In the present weather reporting code there are groups to distinguish between drizzle, rain, showers, and snow, and a few special groups are included for describing such phenomena as hail, freezing fog, and so on. A measurement of rainfall at any land station involves a proportion of water depostion from the atmosphere which is created by orographic effects; hence, the hourly rates derived from such reports do not necessarily apply to sea areas where there are no orographic effects. But some hourly rainfall rates have been derived from measurements with rain gauges made over a period of year at small offshore islands in the Northeast Atlantic. Such hourly rates have been used to make some estimations of rainfall over the oceans using the weather reports from selected ships and in particular from the weather ships. A comparison of the annual rainfall amounts over a period of years at offshore islands with measurements on neighboring coastal plains have almost invariably shown that the former amounts are less by about 10%, due account having been taken of the difference in heights between the respective rain gauges above sea level.

The effects of rainfall on the sea state are particularly obvious in heavy rainfall, such as under tropical cumulus, and reference has been made in Chapter 10 of the quenching effects of such rainfall on hurricane formation due to the elimination of spray. An examination of more than ten years of recorded hourly data at the Weather Stations INDIA, JULIET, and KILO (45 °N 16 °W) in the North Atlantic reveals that continuous heavy rainfall has been reported very infrequently and certainly less frequently than at island stations and still less than at mainland coastal stations at corresponding latitudes to the east. From this it is concluded that orographic features and the heating of the land masses, which accentuate convective processes, are factors affecting drop size to cause heavy rainfall. The parameters describing showers of hail are virtually never used by weather ships or ships of opportunity, and it is probably fair to conclude from this that hail showers seldom occur except close to the coast. However, ships in temperate latitudes do use the parameters for moderate continuous or intermittent rainfall, which assists the placing of fronts. In warm frontal depressions, such rainfall probably does exert considerably modifying influences on sea and swell generation.

13.7 Sequence weather affecting sea and swell development. Many of the points made in the text concerning sea and swell generation are now illustrated in ten sequences of three hourly data from Ocean Station PAPA (50 °N 145 °W) covering the winter period from 20 January 1975 to 1 March 1975. Details are plotted in Figures 51 to 60. Tucker wave meter data were recorded every three hours, and significant wave heights can be considered in conjunction with three-hourly data logged at the weather ship. All times are GMT.

On each diagram, the sequence of wind vectors, which is the most important factor in sea state generation, is plotted in two ways: as a continuous sequential vector diagram; as a sequence of vectors at three-hourly intervals along a straight line. The former method illustrates more clearly any fundamental changes in wind direction after a period of winds from a particular quadrant, and the second method shows veering and backing of winds with passages of fronts. Both methods have advantages and disadvantages. The former takes up much space, and the latter becomes confusing when winds remain for any length of time in an easterly or westerly direction.

In addition to the plot of significant wave height against time, the dry bulb and wet bulb temperature sequences are plotted using an inverse scale. An inverse scale illustrates how wave heights tend to increase as temperature and humidity fall. Wet bulb temperature was used in preference to dew point since actual recordings to 0.1 °C were available. The important frontal passages have been marked along with well-defined periods of rainfall. The full weather sequence has not been given since it would overcrowd the diagram with too much detail.

We should appreciate that the analyses concern data from one point and that no account is taken of the effects of swell from distant storms. Such swells from extraneous causes may make a sensible contribution to the significant wave height. Allowance for these effects can only be made by considering synoptic sequences and studying the actual spectra. In some instances it can be deduced from the peak wave periods, for when these are large, it is an indication that considerable swell is present.

Some other points of interest are:

Significant wave heights exceeding 25 feet. Significant wave heights exceeding 25 feet are to be found in Figures 51, 53, 55, and 57. In each of the four cases, there was a marked acceleration of wind following a veer of wind, usually to the northerly quarter. Cold or polar or modified arctic fronts crossed the area near the maximum sea state conditions.

Figure 53 shows the highest value recorded of over 30 feet, which developed in a cold accelerating northwest wind. In almost every case, the maximum is reached early in the development stage, and there is some decrease in significant wave height in the next few hours without any marked decrease in the wind force. This point has been made many times in the text concerning the consequent effects on the steepness factors which are usually greatest in the early stages of development when maximum height is achieved before maximum period.

The effects of rainfall. The effects of rainfall are to be found in Figures 57 and 59, particularly the latter. On the afternoon of 24 February, the wind accelerated to over 40 knots and exceeded that value for more than six hours. It followed a considerable backing of the wind by 70°. Althought the winds remained at 40 knots or more for several hours, the significant wave height barely reached 20 feet. Inserting wind speeds into the empirical formula for wave height give heights in excess of 25 feet.

The winds were from the south to southeast quadrant and generally warm, which would indicate less bite on the water surface. However, continuous rain was falling at the station for over six hours, and this was probably the main cause why seas were not higher.

In Figure 57, strong southerly winds prevailed following a backing of the wind of approximately 90°. The significant wave height was less than 15 feet, although wind speeds were constant in direction and between 30 and 35 knots. Again, continuous rain was recorded for eight hours, and this probably exercised considerable modifying influence on the sea state.

The effects of swell from distant storms. The contribution of swell from a distant storm can be clearly seen in Figure 51. On 21 January, the significant wave height rose to a maximum of 16 feet whereas the wind speed fell below 20 knots soon after midnight on 20 January. Winds of the order of 15 knots prevailed for the next 24 hours, insufficient to account for the rise to a maximum of 16 feet late on 22 January. An examination of the wave spectra shows that throughout the day the peak period was greater than 12.5 seconds, which is an indica-

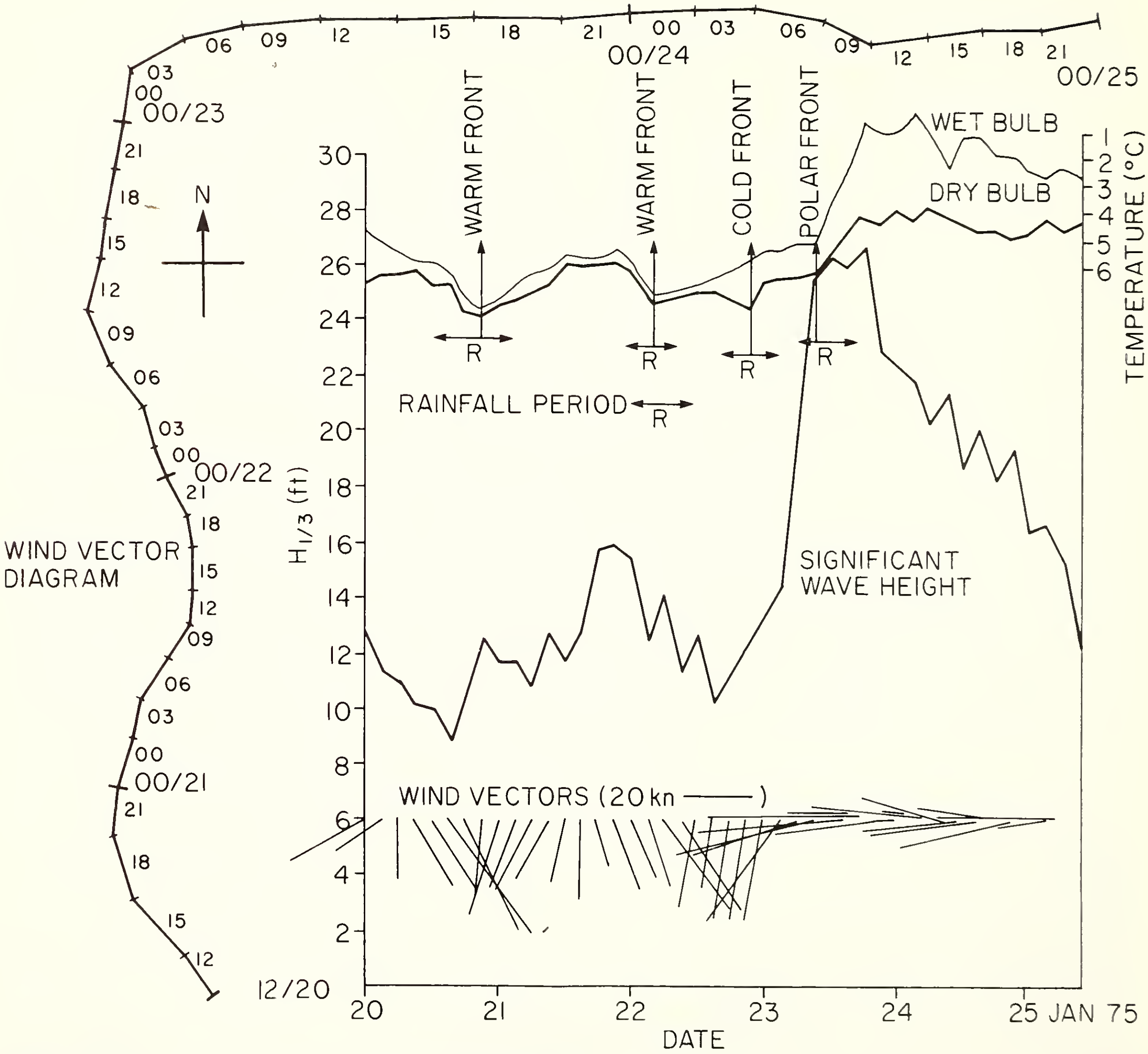


Figure 51 - Ocean Station PAPA, 20-25 January 1975.

(a) The principal feature is the rise to a maximum significant wave height of 26 feet about midday 23 January. It followed a steady increase in wind speed following a veer of wind through more than 100°. The maximum height occurred soon after the passage of a polar front.
(b) The rise which occurs after 1200/20 can be accounted for by an increase of wind speed, but the similar rise on 22 January in moderate southerly winds was due to swell from a distant storm. This can be deduced from the long peak period of 13.7 seconds (not shown in the diagram).

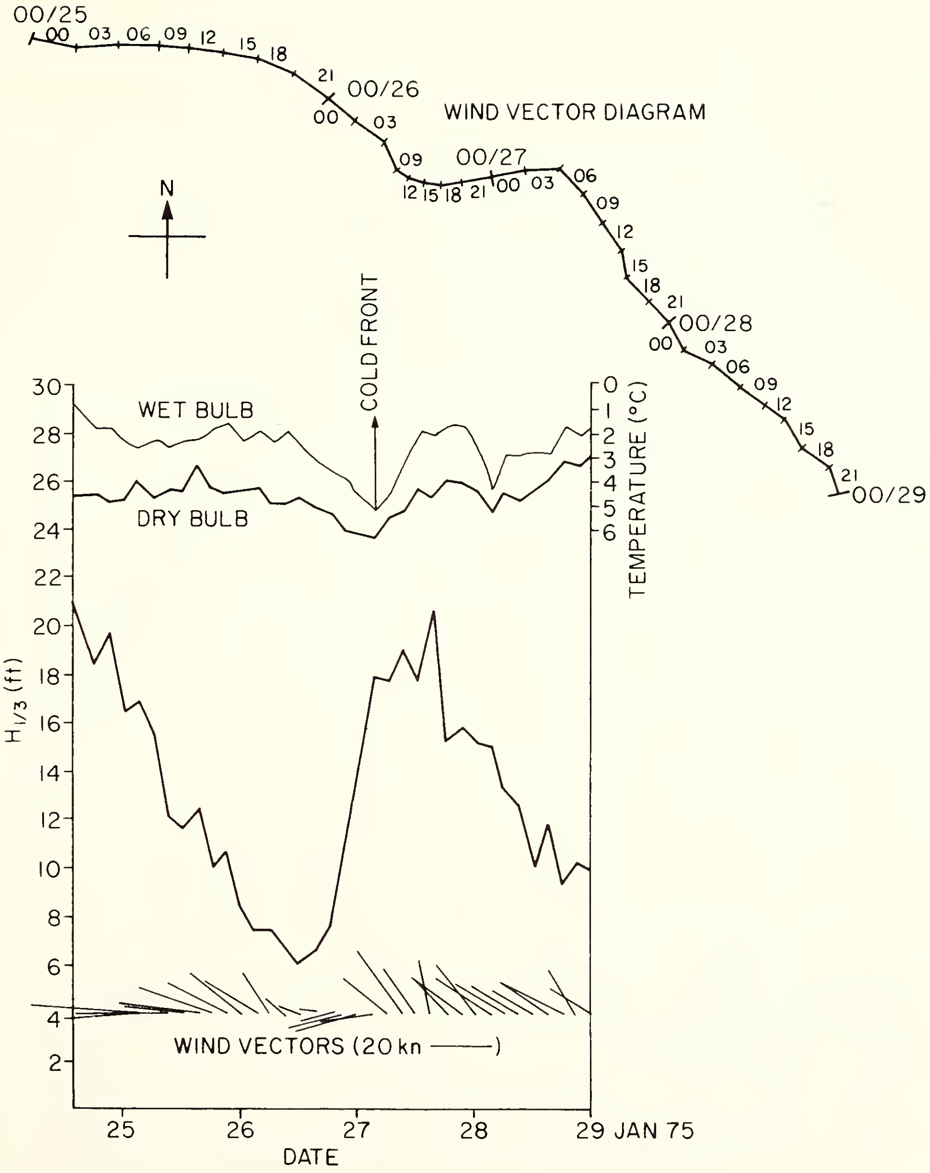


Figure 52 - Ocean Station PAPA, 25-29 January 1975.

(a) The maximum wind recorded in the period was only 24 knots, although winds were generally north of west and cold.

(b) The marked increase in significant wave height to 20 feet occurred between 2100/26 and 1200/27 with the maximum following a cold front.

(c) At 0600/27, the wind veered 60° to its former direction, and this could be the main reason for the first of the two peaks in the significant wave heights graph between 0000/27 and 1500/27; the second peak probably being due to an arctic front or line squall.

(d) Rainfall reports in the period were confined to short spells on 25 January and a half-hourly period at the cold frontal passage at 0600 on 27 January.

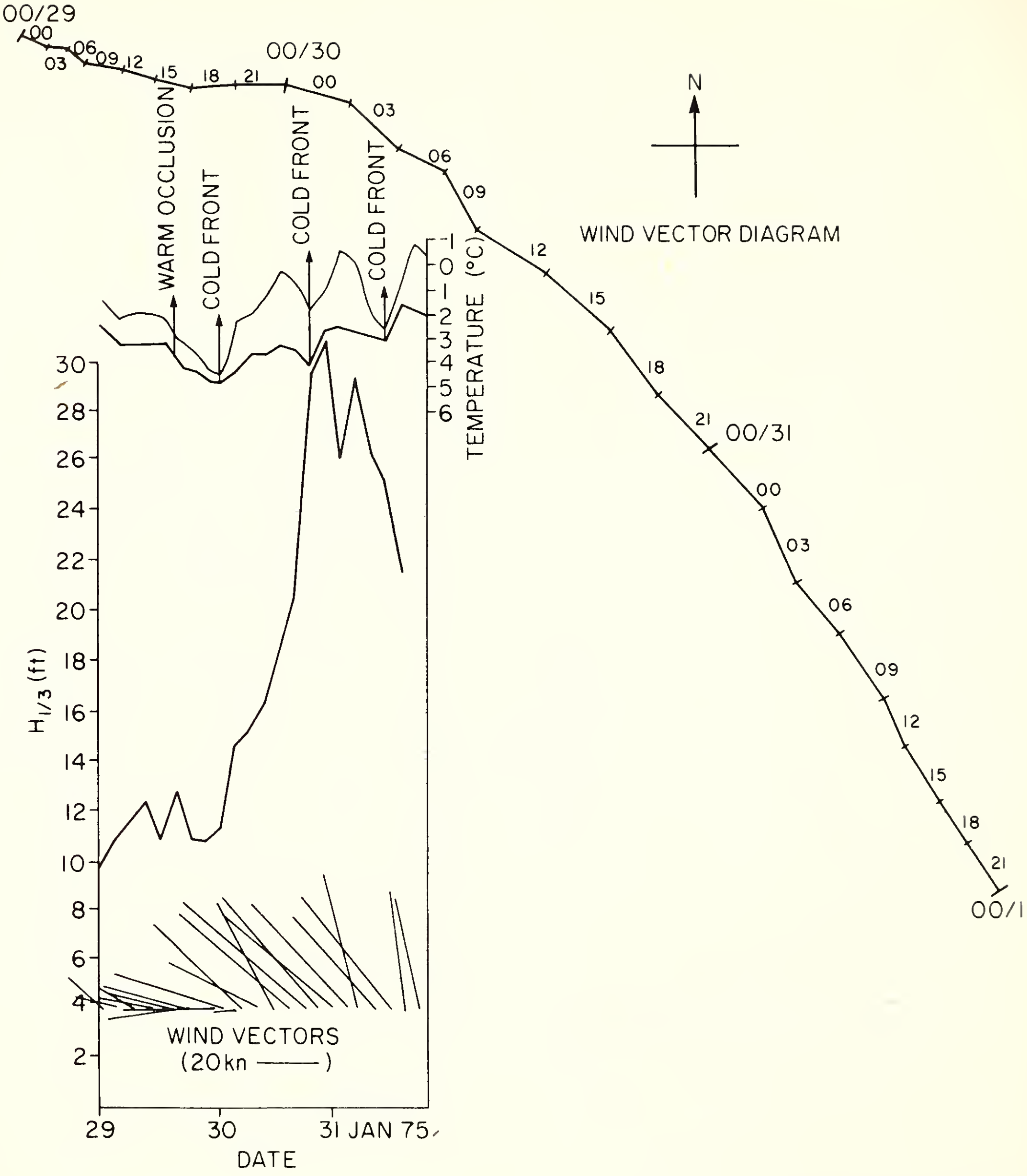


Figure 53 - Ocean Station PAPA, 29 January - 1 February 1975.

(a) The marked increase in significant wave height to over 30 feet at 0000/31 can be attributed to the increasing wind strength to gale force from the northwesterly dirrection.

(b) There was very little overall wind change in either speed or direction after 0900/30 through 0000/1 February, but the significant wave height diminished considerably from its maximum around 2100/30 January. The secondary maximum in the early hours on 31 January is attributed to the veer of wind of 30° in a squall.

(c) A number of fronts crossed the area, mainly cold fronts or line squalls. Reported rainfall was mostly showers.

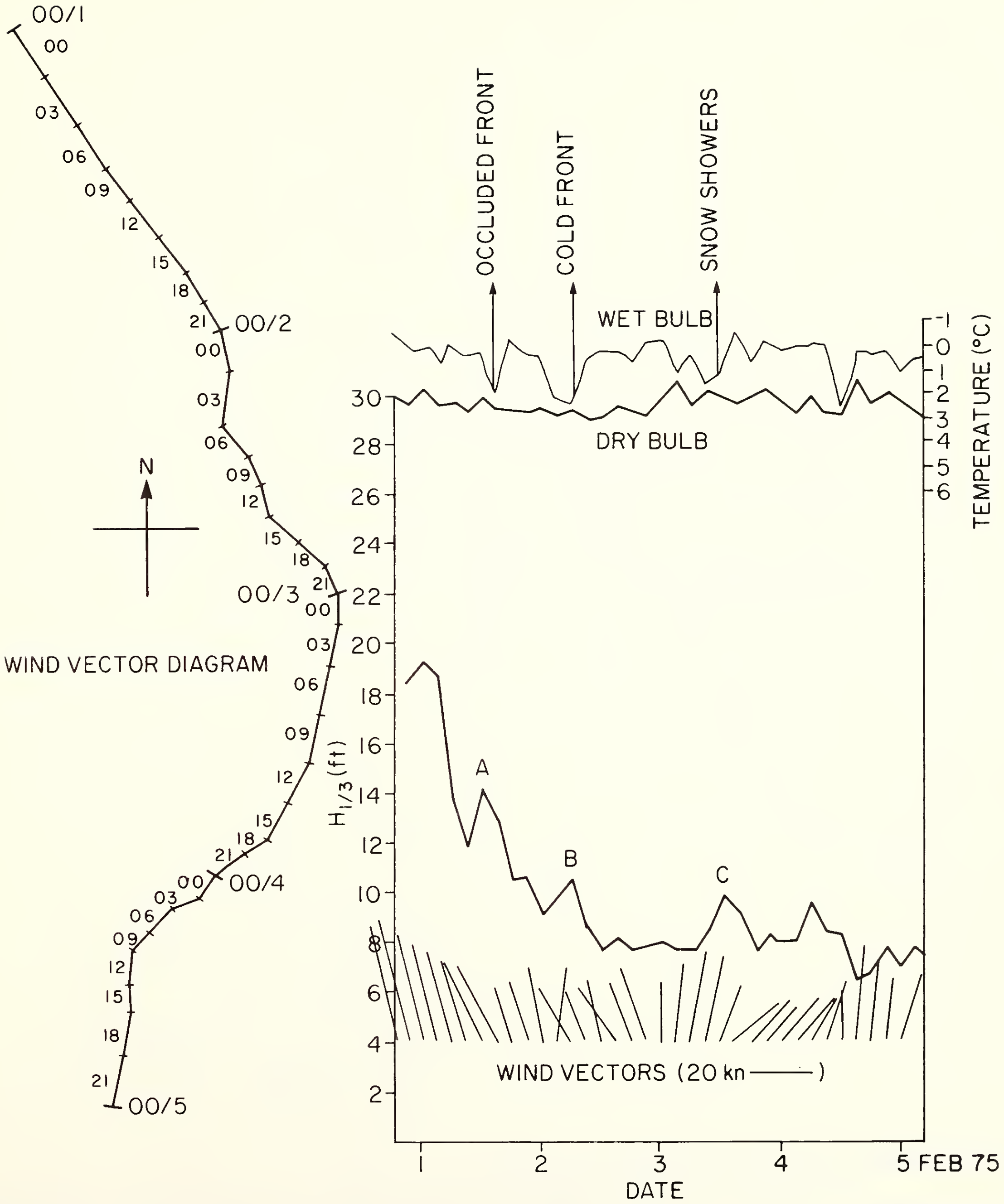


Figure 54 - Ocean Station PAPA, 1-5 February 1975.

Although the winds throughout this four day period continued from a northerly quadrant, they were never more than 25 knots, and the significant wave heights diminished after the gales of 30/31 January. Peaks A, B, and C can be accounted for by cold fronts or line squalls often accompanied by hail or snow showers in the relatively very cold air mass.

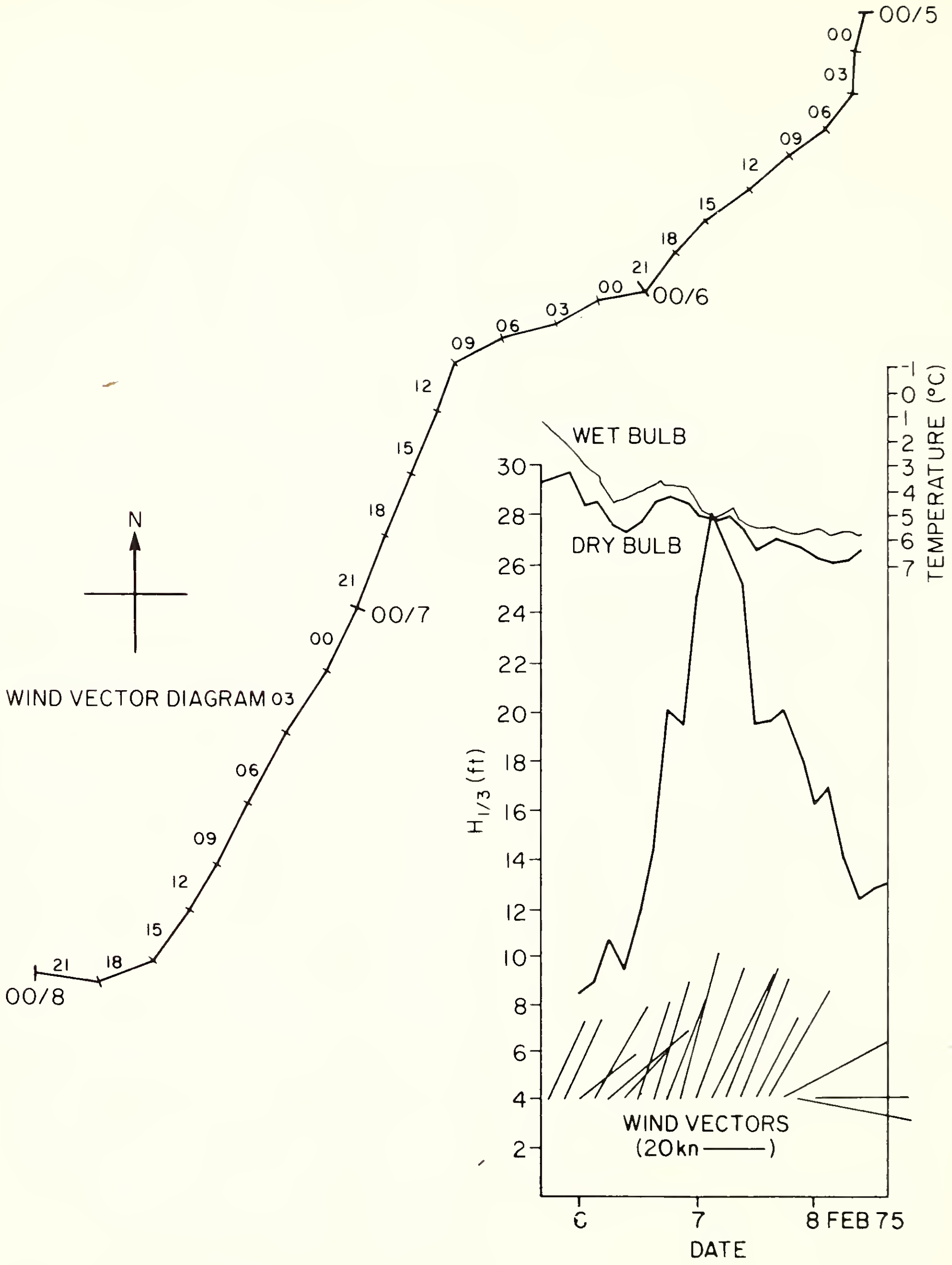


Figure 55 - Ocean Station PAPA, 5-8 February 1975.

(a) The significant wave height increased markedly about 0900/6 February following a steady increase in wind speed to gale force.

(b) The maximum seas occurred about 0300/7 February; thereafter, the significant wave height fell, although the winds remained strong for a further 12 hours.

(c) On average, winds were stronger on 7 February than on 6 February. The fall in significant wave height is arrested during the afternoon of 7 February - probably due to the veer of 40° which occurred in mid-afternoon.

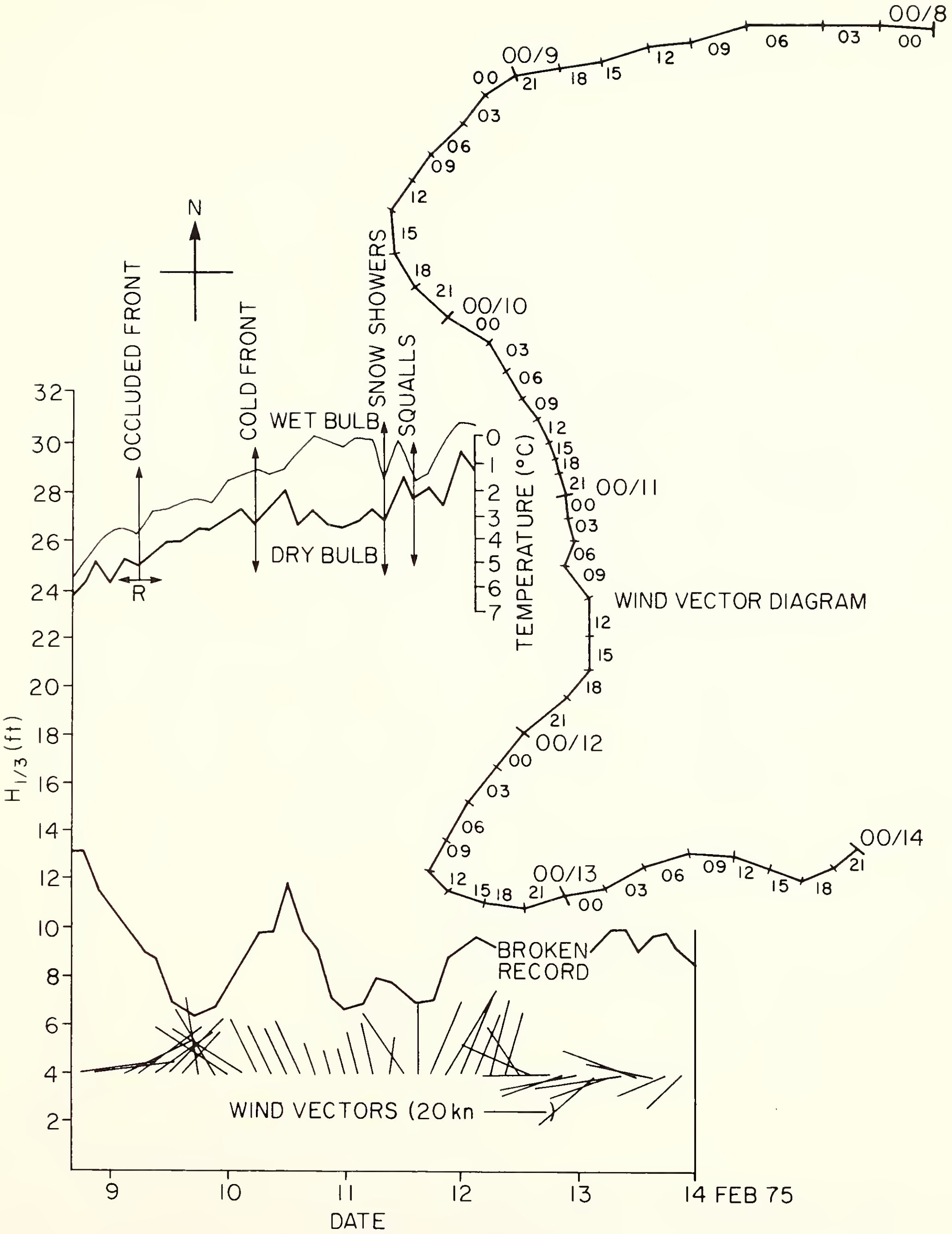


Figure 56 - Ocean Station PAPA, 8-14 February 1975.

The increase in significant wave height, which started in the afternoon of 9 February and continued to approximately 1200/10 February, coincided with the backing of the wind. The wind speed throughout is decreasing. Temperatures are low and wind speeds 20 knots or less.

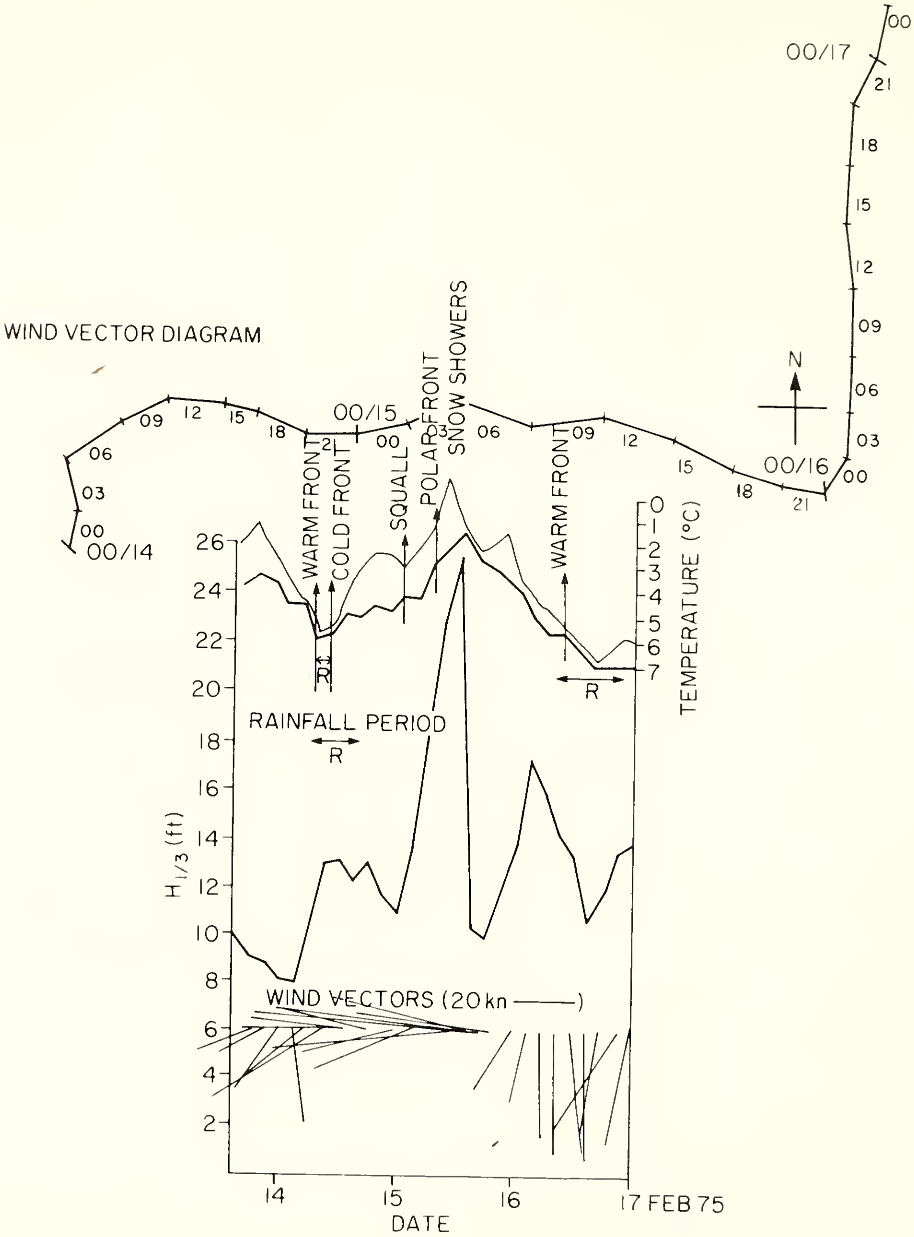


Figure 57 - Ocean Station PAPA, 14-17 February 1975.

(a) The first increase on 14 February is perhaps entirely due to the change in wind direction.
(b) The marked increase early on 15 February is due to wind acceleration from the west.
(c) The increase late on 15 February does not appear to be due to an increase in wind speed but to the wind backing over 90° to the south.
(d) From 0900/16, continuous rain was falling, and though the wind speed was 30-34 knots, significant wave height was only 12 feet.

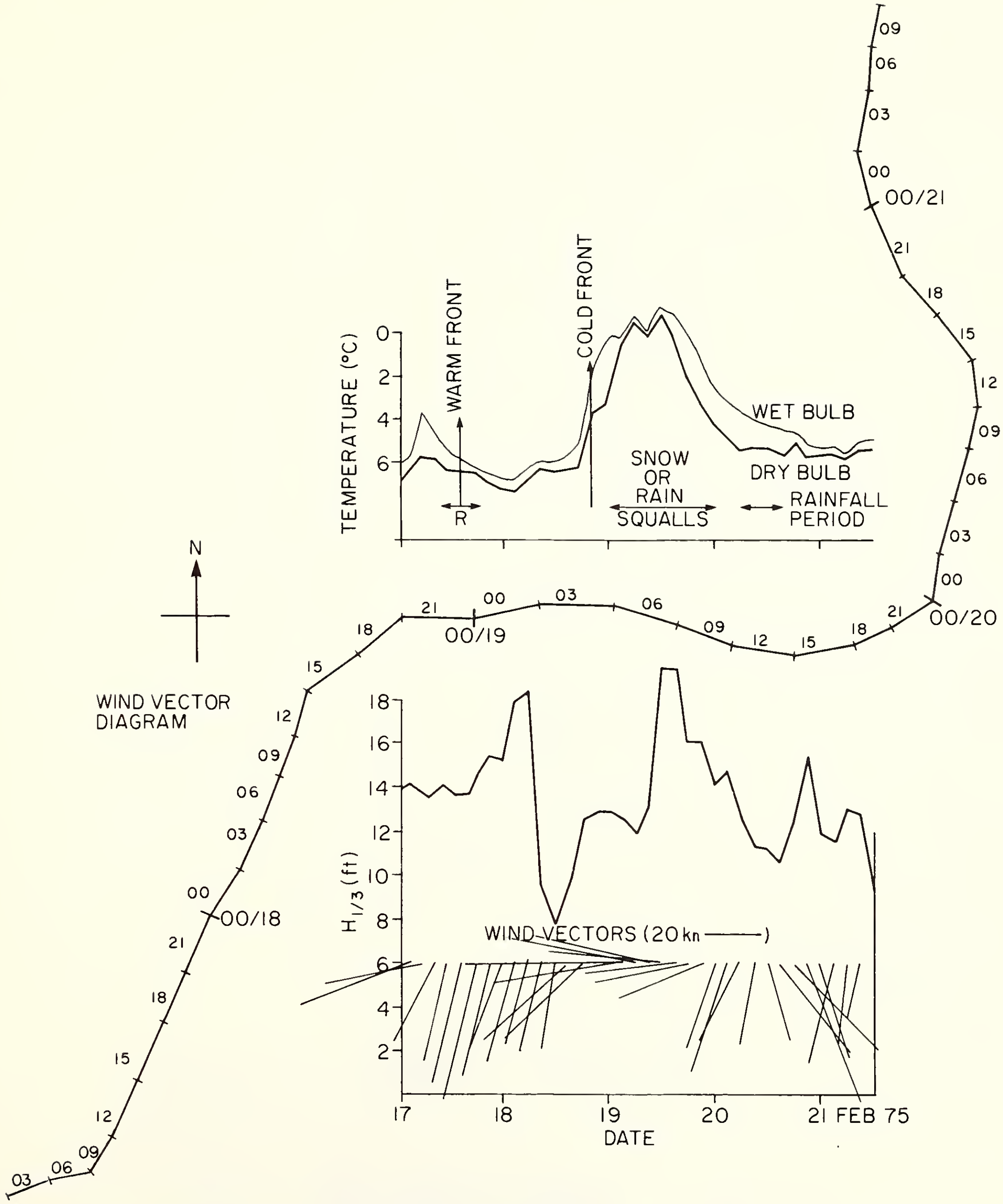


Figure 58 - Ocean Station PAPA, 17-21 February 1975.

(a) The first marked increase at 2100/17 was due to the acceleration of the wind starting mid-afternoon on 17 February.

(b) The heights decreased early on 18 February but picked up again with the wind veer at 1200, reaching a maximum near 0000/19.

(c) A further veer and an increase followed the cold frontal passage.

(d) Subsequent peaks on 20 February are probably due to various combinations of changes in wind direction and acceleration.

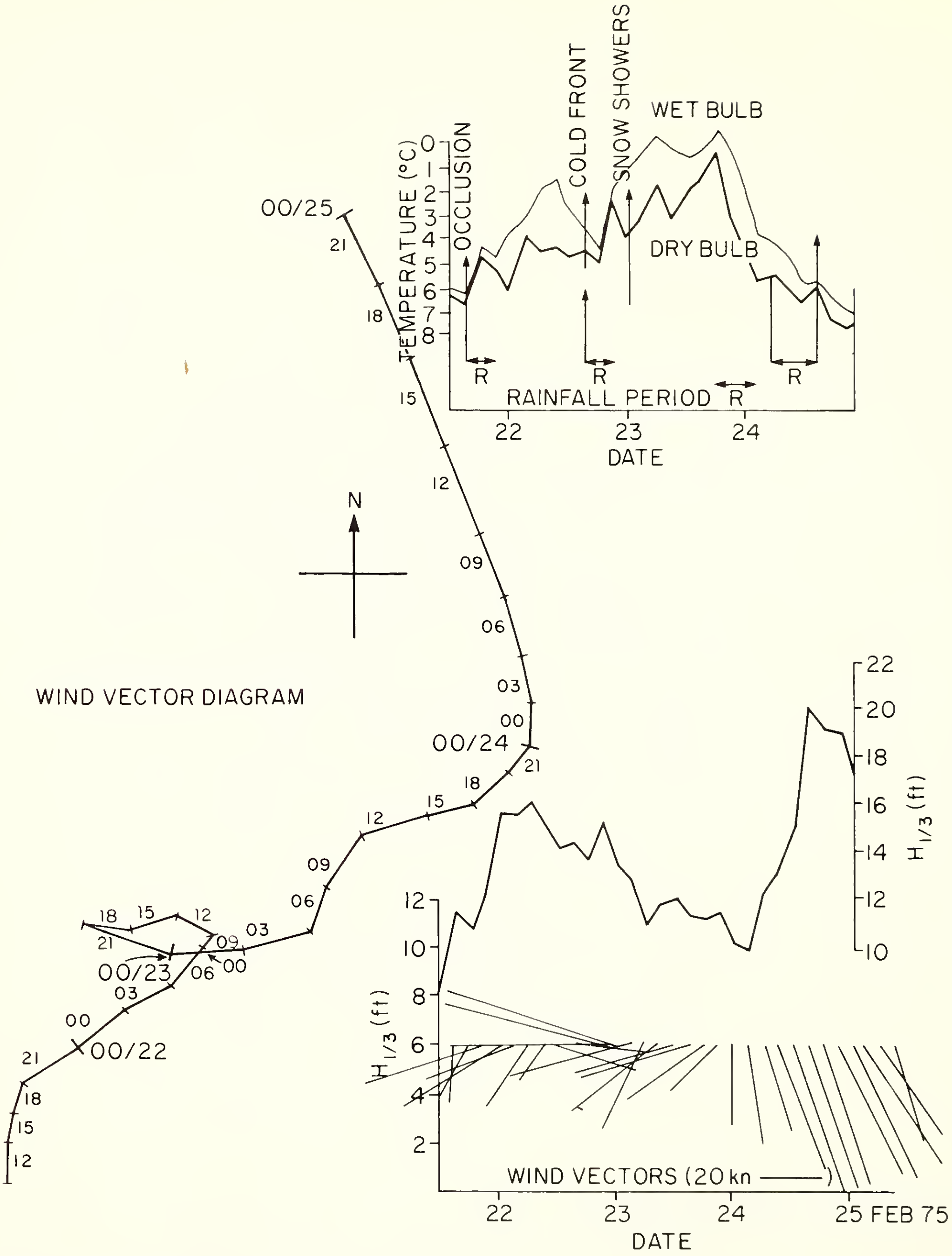


Figure 59 - Ocean Station PAPA, 21-25 February 1975.

(a) The rises between 1200/21 February and 1800/22 February were due to combinations of wind direction changes and wind speed increases.
(b) The more marked increase in wind to gale force on 24 February did not cause the significant wave height to exceed 20 feet. This appears to be a case in which continuous rainfall was a restraining factor.

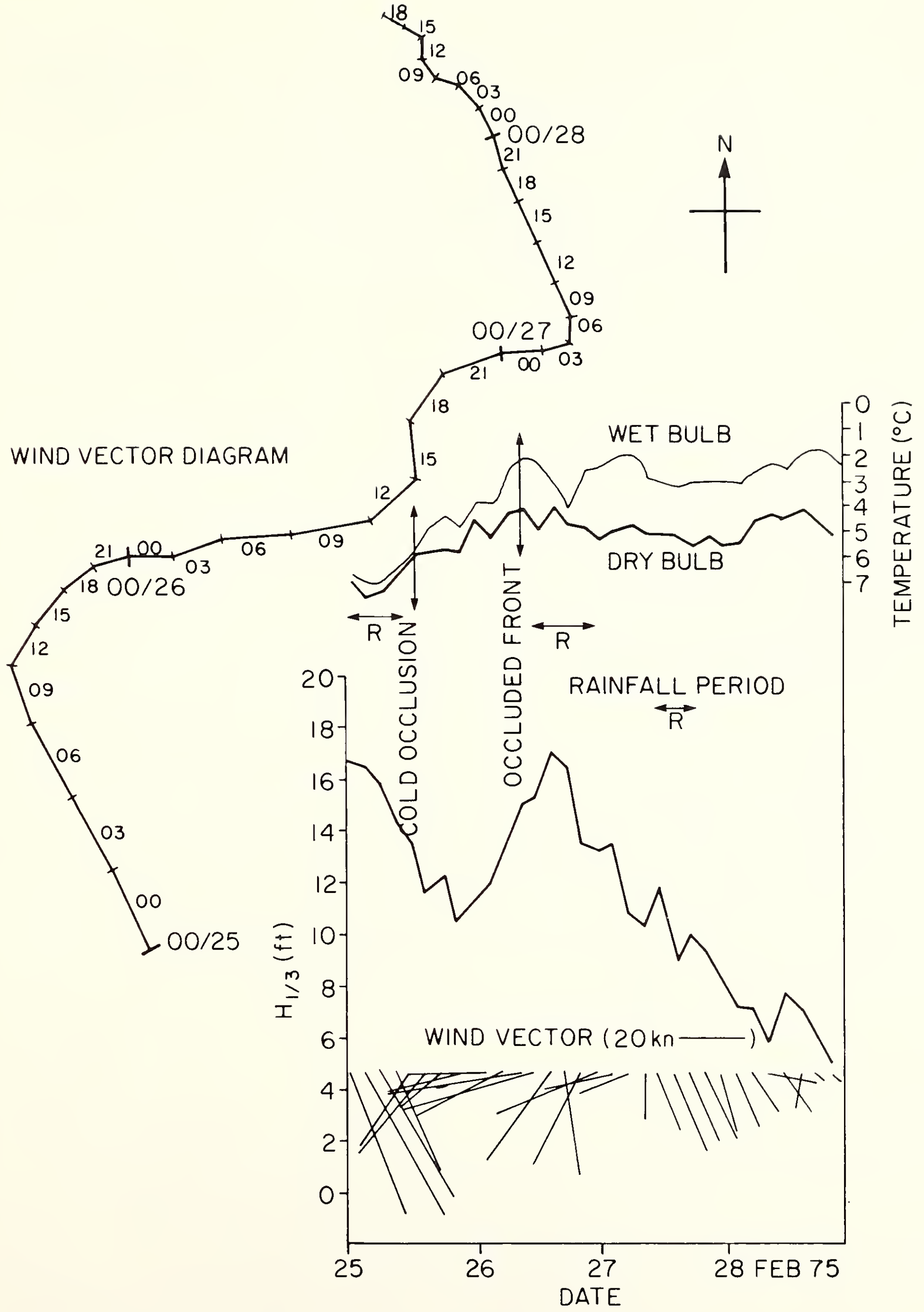


Figure 60 - Ocean Station PAPA, 25 February - 1 March 1975.

(a) Although the wind remained at gale force from 0000 to 0700 on 25 February, the significant wave height steadily decreased, probably due to the continuous rainfall in the period.
(b) The rise to a maximum of 17 feet on 26 February can be attributed to wind direction changes and the passage of a front.

tion of swell from outside the area of PAPA.

13.8 Sea and swell in pack ice. Raising and lowering floating objects and in particular, pack ice, requires energy; therefore, some of the energy transfer from atmosphere to ocean by the winds in a storm becomes devoted to this purpose. The energy required is obtained mainly at the lower end of the energy spectrum, which results in lowering the seas but having relatively less effect on the swells. The orbital motions of the water particles are considerably affected in the seas of short wave lengths but less so in the swells. Ships, when first transitting pack ice boundaries in heavy swells, are susceptible to hull and propeller damage from the movements of the ice. But once inside the outer lines of ice, the swell is also considerably reduced and the waters are comparatively calm.* Virtually, the pack ice forms a protected harbor for a ship.

**Ed. note: Depending on the amount of ice and the height of the swells entering the ice pack, the movement of the ice floes can still be considerable, even more than 15 miles inside the outer lines of the ice.*

CHAPTER

14

BASIC CONSIDERATIONS FOR PREDICTING MOVEMENT OF WEATHER FRONTS

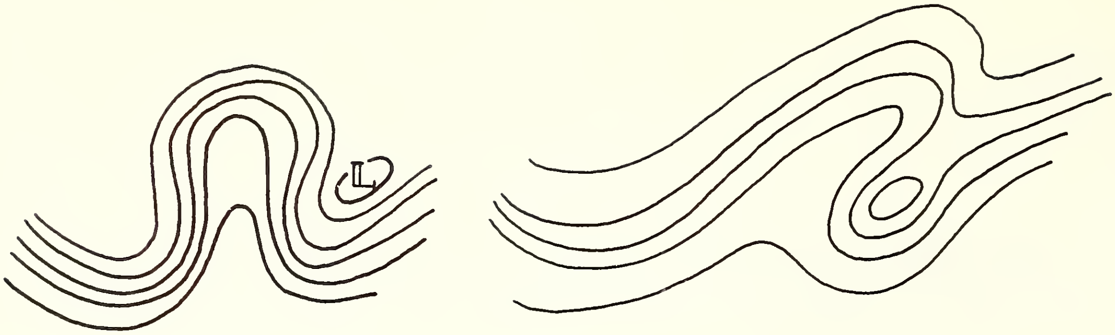
14.1 Introduction. It will have become obvious from the previous chapter that one of the principle requirements for forecasting seas of operational significance depends upon the capability to identify and forecast the progress of cold fronts of all types over the oceans. It may be considered as a specialized aspect of weather forecasting and one which is more heavily dependent than others on the surface synoptic chart since the leading edges of cold air masses can be located from discontinuities, particularly of temperature and dew point. The large number of observations on surface level charts facilitates the task. But as with all forecasting problems, the surface chart alone is not sufficient, and some consideration of the pressure patterns at all levels must be taken into account, especially when forecasts for several days ahead are required. Hence, some mention of upper air charts is necessary.

14.2 Rossby waves. Meteorologists, in preparing forecasts, give considerable attention to the pressure pattern charts derived from radiosonde data at 500 millibars. This roughly corresponds to a height of 5,000 to 6,000 meters above the sea surface. At this level, which is approximately ''half-way'' up through the atmosphere (when considered in pressure units), many of the complications caused by frontal discontinuities in cyclonic disturbances are smoothed out, and the large scale flow patterns of the air around the hemisphere are simplified and revealed. The lines of flow corresponding to isobars on surface pressure level charts are called contour lines and join points of equal height above the surface. It is also customary on the same charts to join points of equal ''thickness'' -thickness being defined as the difference in height between the 1,000 and 500 millibar levels. These lines often indicate the paths which lows will follow and are an indication of the relative warmth of the lower atmosphere.

A characteristic of such flow patterns in the temperate latitudes at 500 millibars are crude wave forms with wave lengths of the order of 5,000 to 15,000 kilometers. These are called Rossby waves after the scientist who first investigated them. They provide the forecaster with the best guide as to the probable direction of movement and possible development of lows; thus, they are very important factors in weather forecasting. It is not the intention to go into the theory of Rossby waves since much of it demands a knowledge of vector mathematics. Refer to any good textbook on meteorology for further detail.

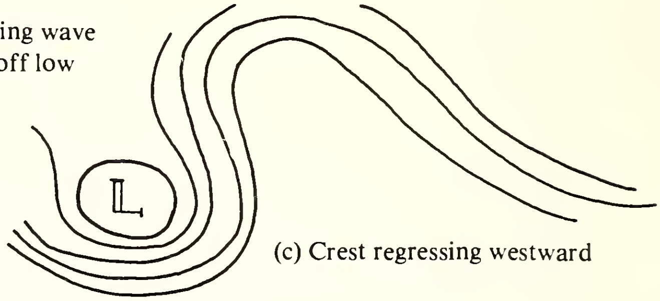
Rossby waves usually exhibit some degree of skewness and varying degrees of amplitude. One typical formation is designated as the omega formation since it approximates in shape to the Greek letter of that name. Jet streams occur where the contour lines are closest together. Three typical wave patterns are shown in Figure 61.

Polar or major cold fronts are often associated with the well developed meridional or north-south flow on the eastward flank of the well-defined Rossby wave formations. In particular, areas where the contour lines at the 500 millibar level have a marked north-south orientation and are closest together (*i.e.,* in the neighborhood of the jet streams) will be those areas where depressions or polar lows are most likely to form with associated cold fronts in the circulations. Therefore, the first consideration in the forecasting process must be to consider the flow patterns at 500 and 300 milibars since these will indicate the broad areas where such outbreaks of very cold



(a) Omega formation

(b) Overturning wave
with cut-off low



(c) Crest regressing westward

Figure 61 - Various types of Rossby waves.

or arctic air are to be expected. The orientation of the Rossby waves is important, and whenever possible, a distinction should be drawn between those waves with an overturning crest in the forward (*i.e.*, eastward) direction and those which lean backwards toward the west as typified in Figures 61b and 61c respectively.

The forecaster needs to look first for the typical omega formation of the Rossby wave on the 500 mb charts and then to identify those waves progressing and tending to overturn in the manner of a breaking wave. These formations often lead to the creation of a cutoff low in the upper atmosphere with the vortex extending in either direction in the vertical.

The omega-type formation provides the source of energy necessary for vortex formation. Here, an analogy may be drawn with surf riding in which the surf rider derives the energy for his forward propulsion just ahead of the progressive crest. In the same way, the maximum energy in a progressive Rossby wave is located near the leading edge of a crest. As such waves move from sea areas into continental regions (*e.g.*, over Europe or northwestern Canada in winter), some entrainment of air from ice covered surfaces onto relatively warm sea frequently occurs.

Large amplitude Rossby waves are usually coincidental with marked anticyclonic circulations at all levels of the atmosphere, and their development can be considered simply as a development of highs. But anticyclones or highs can develop from various causes, which requires some further definition of such systems.

14.3 Anticyclones. Anticyclones are seldom given the same rigorous treatment by meteorologists as are frontal depressions, but their importance is equally great, and their role cannot be fully understood unless some distinction is drawn between the various types and the causes of their development. In general, areas of high pressure derive from cooling processes as a result of radiation of heat into outer space. Some distinction should be drawn between the various radiating surfaces.

Cooling may take place principally as a result of radiation from the cloud tops in the high atmosphere. As the air cools, the density increases and the air sinks, which in turn heats it by compression. Thus, the high pressure cells of the subtropical regions are formed as a result of subsidence from the upper atmosphere. For obvious reasons, such anticyclones tend to be located as permanent features over the oceans areas. In the Southern Hemisphere, the systems are very stable and predictable and occupy the centers of the oceans between the large land masses. In the North Atlantic, one cell only can usually be identified (the Azores High). Occasionally, two such cells appear in the North Pacific.

Intense radiation into outer space occurs from the snow-covered land masses with high albedo during winter months. This leads to the accumulation of cold air masses at surface level and the creation of intense anticyclones with very high central pressures. If the accumulation becomes too great, some of the air mass moves off the continents as a low level flow giving rise to a third type of anticyclone -the migratory anticyclone. The leading edge of such moving or migratory anticyclone will be a cold front, and polar or arctic fronts may be embedded in the air masses in the rear.

14.4 Blocking anticyclones. A fourth type may be defined as a blocking anticyclone. It is difficult to find an agreed definition for a blocking anticyclone, but it is a term used by meteorologists to designate a high pressure area which develops in the temperate zones and impedes or blocks the regular flow of air from west to east. This definition or designation for one particular type of anticyclone is perhaps unfortunate since all anticyclones exercise a blocking role in one way or another. The subtropical high pressure areas function so as to block the flow of cold surface air on the route from arctic regions towards the equator. In this function they constrain the air masses to flow eastwards along their pole-side boundaries until a col is reached between two successive cells. The subtropcial high pressure cell is only a special case of a blocking anticyclone, the blocking action being concerned with meridional as opposed to zonal flow.

Variations in intensity of the subtropical high pressure cells result in variations of wind speed in the tradewind zones on their eastern boundaries. The cell functions like a bellows, giving rise to irregular increases and decreases in the strength of the trade winds. This has the result of creating fronts within the air-stream itself, and the squall lines are marked features of the flow. The basic principles of sea and swell generation apply in these areas where there is is a fetch in a sensibly constant direction for thousands of miles. The air mass is relatively cold in relation to the sea surface temperature, and intensification of the subtropical high pressure cell often gives rise to a marked swell in the doldrum belt.

It is not the intention in this book to go into detail as to the nature of blocking anticyclones. Their role and formation process are not fully understood by meteorologists, probably because of the imprecise definition. The view is held that they are a form of migratory anticyclone which may become linked with either a subtropical or a continental anticyclone. It is sufficient to say that in the Northern Hemisphere they persist for an average of about 15 days; although some may last for more than 30 days. They occur in preferred places -one being over Scandanavia at an average latitude of about 60°N. In the early days of formation, they usually drift westwards. One sign that they are about to decay is that the western movement has ceased and the anticyclone starts to move eastwards.

In the Southern Hemisphere, blocking anticyclones are comparatively rare features and usually have a life of less than one week.

14.5 Satellite analysis.* Much frontal identification and monitoring of fronts is now undertaken in analysis centers using satellite imagery. The arctic air masses may sometimes be identified from the parallel cloud streets which typify very cold air. However, satellite pictures can be misleading for this particular type of identification. Cold air masses entrained by depressions from off frozen plateaus (*e.g.*, from the interior of Alaska, from southern Europe in winter, or from Antarctica) have a very low water vapor content; it may be almost nil. Also, a degree of subsidence is involved from the levels of the plateau to sea surface. Hence, cloud formations are often entirely absent in the initial stages of the passage of the air mass over the sea, a minimum fetch being necessary before cumulus clouds can develop in the unstable air. This is particularly noticeable in certain areas,

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Ed. note: Two excellent books, well illustrated with numerous pictures along with explanatory text, are used by the U.S. Navy for interpreting weather satellite images: Fett, Robert W. and Walter F. Mitchell.* **Navy Tactical Applications Guide - Vol. 1 Techniques and Applications of Image Analysis. *U.S. Naval Document No. NAVENPREDRSCHFAC Technical Report 77-03 and Fett, Robert, W., et. al.* **Navy Tactical Applications Guide - Vol. 2 Environmental Phenomena and Effects.** *U.S. Naval Document No. NAVENVPREDRSCHFAC Technical Report 77-04. Naval Environmental Prediction Research Facility, Montery, California. 1979. (Books are unclassified.)*

such as the Gulf of Lions in mistral conditions. It is common to find a cloud-free area extending for up to 100 miles from the coastline. It cannot be assumed from this absence of cloud that no cold fronts are present since they can be readily identified from dew point temperature discontinuities at surface level. The very rough seas encountered in winter in the Gulf of Lions are often associated with frontal passages in almost cloudless skies. The absence of cloud in tempestuous weather may seem unusual. Considerable quantities of spray may impair the otherwise perfect visibility.

14.6 Surface synoptic charts. For detail, the forecaster must rely on the surface synoptic chart, and here the identification of polar fronts demands special study. The primary cold front (*i.e.,* the one on which the center developed) may be of less importance from the sea and swell aspect than the secondary cold or polar fronts embedded in the cold air mass in the rear. Much depends on the tightness and curvature of the pressure gradients in the rear of the depression and the degree of modificaiton which the cold air mass has undergone. Any change of wind direction may also be very important. The point is made that each front needs to be considered on its merits whether it be a primary cold front, a polar or arctic front, a bent-back occlusion, or a katabatic outflow.

Precise categorization of fronts in this way may vary from analyst to analyst, but the difference of view will be largely academic. The salient points for the forecaster to identify are the signs of cold fronts originating from whatever cause.

14.7 Isallobaric charts. Forecasting changes in the wind speed and direction or determining the acceleration of the wind is perhaps the most important element in short-term sea state forecasting. Wind acceleration is a reflection of changes in atmospheric pressure resulting from the intensification of pressure gradients. Some indications are obtained of such trends from isallobaric charts which display isopleths of barometric changes over the last three hours.

Unfortunately, isallobaric charts are difficult to construct over sea areas. This is because the pressure tendencies reported by ships first need a correction factor applied to them to account for the movement of the ship during the three-hour period considered. Thus, a ship steaming straight across the center of an intense low that is moving at right angles to the isobars will have two components in the barometric change of pressure: a fall due to the movement of the depression itself and a fall brought about by the movement of the ship towards the center.

Before drawing isopleths of barometric tendency, it is first necessary to analyze the surface synoptic chart as accurately as possible, using smoothing techniques to deduce the spacing between the isobars in the vicinity of the ship. It is then necessary to use the ship's reported speed and direction of travel to estimate how much barometric change has resulted from the movement of the ship. Subtracting this amount from the reported change gives the true barometric tendency. This is a tedious and time-exacting process to carry out for every ship report on a synoptic chart and seldom is sufficient time available to undertake the task satisfactorily. Nevertheless, the experienced forecaster will recognize the potential for rapid development of a low system and will draw such isopleths, if necessary, over a limited area, not only to determine the likely direction of movement of the center, but also as an aid to estimate the degree of deepening which will continue. It is only by such procedures that the best wind forecasts for six, nine, or twelve hours ahead can be obtained. As has been shown, once such accurate forecasts of wind speed are available, an excellent estimate of significant wave heights follows.

14.8 Pressure and dew point. Since cloud and precipitation are often absent in arctic or antarctic fronts or on the leading edges of katabatic flows off icy plateaus or down mountain valleys, a forecaster must give considerable attention to barometric pressure tendency and temperature discontinuities. Falls in the dew point temperature are particularly important. A ship or an oil rig operating offshore should always be alert to the dangers of steep seas associated with polar fronts; the first indication of which may well be a squall. If observations are available from stations in the up-wind direction, some prior warning may be obtained by keeping a close watch for any appreciable falls in dew point or sudden rises in pressure.

In arctic regions, a blizzard will be a good indicator. This is not necessarily inconsistent with the statement made earlier that cloud or precipitation are sometimes absent with polar fronts. Over snow covered surfaces, katabatic flow in particular may cause considerable quantities of drifting snow to fill the air. It is not always appreciated that the apparent movement of a cold anticyclone from west towards east on a synoptic chart in the rear of a depression may be a deceptive movement. The flow of the cold air mass from north towards south results in a pressure increase as the depth of the air mass from the surface upwards increases. Thus, as a cold air mass moves into a col between two subtropical high pressure systems, the trade wind flow is augmented and increases. On the synoptic charts, it appears that the subtropical high extends eastwards as pressure rises in the trade wind zone due to cooler temperatures.

An area where such circumstances occur, one of particular importance to shipping, lies off the western coast of Canada, particularly in the inland waterways between the islands and the mainland.

Depressions occasionally cross the Gulf and move inland into Canada and are followed by a cold anticyclone as a result of the north-south flow of entrained air from the higher ground of eastern Alaska and Northwest Canada. Such circumstances frequently trigger katabatic flow down the fjords and inlets and channel the flow of air over the inland waterways to the east of islands, such an Vancouver Island in British Columbia, which are mainly orientated in the north-south direction. Pressure rises as a result of this airflow to lower latitudes, and the apparent migration of the anticyclone eastwards is deceptive.

14.9 Forecasting katabatic winds. Flow of cold air down mountain and river valleys out over the open sea in winter has long been recognized as a major hazard to shipping. Throughout history, local winds of this nature, the mistral, the tramontana, the bora, and so on, have caused damage and destruction both on land and on sea in the Mediterranean and are feared by farmers and seamen alike. They are difficult to predict because they are essentially very dry, cold fronts of limited width with channeled flow. They behave as jets with a Venturi effect. In some areas of the Mediterranean, the jet may be experienced in a localized belt of width of the order of perhaps no more than 25 miles for a distance of 100 miles from the coast. A distinction is drawn between such outflows and the entrainment of air by the scouring action of transitory depressions over major ice-shelves, such as occur in the Weddell and Ross Seas in Antarctica and the Bering Sea and the Davis Strait in the Northern Hemisphere. Both are a menace to shipping, but the latter occur on a broader front. Katabatic winds are much more localized, more destructive, and more difficult to predict with any degree of accuracy.

Locally, the knowledge of generations has resulted in the use of some single observer indicators, but the general absence of significant cloud types, which normally play some part in single observer prediction of a weather change, make such local rules less reliable than normal. Nevertheless, it will pay the yachtsman or small boat fisherman to make himself familiar with any such local knowledge if the waters are foreign to him. This information is often listed in the pilot sailing instructions for the area. However, there are many such waters, often inland waters between islands and the mainland, where the information is difficult to obtain. There is a need for its collection and promulgation in some suitable booklet.

It is frequently very difficult to predict the direction of wind flow and the strength of the wind in a strait between islands from the normal synoptic chart sequences. Local meteorological offices have often developed empirical rules to aid the forecasting of such events. The wind blows parallel to the strait in one direction or in the reverse direction. Many examples come to mind, but one well known to seamen is the Strait of Gibraltar, lying between the mountains of Spain and the Atlas mountains of North Africa. Although the pressure patterns on the synoptic chart may indicate north-south or south-north flow, the wind will almost invariably channel through the Gibraltar Strait in either an east-west or west-east direction. Empirical rules usually based on pressure gradients between reporting stations have been developed locally be meteorologists enabling them to forecast which it will be.

The empirical rules for forecasting localized wind flow vary considerabely in character, but are almost invariably based on pressure differentials between selected reporting stations. These differentials will not be called pressure gradients since the formulas often have been discovered by trial and error over a long period of time and sometimes have no obvious physical explanation. Occasionally, winds flow counter to the principles of gradient flow. Hence, no attempt will be made to list them, but their value must not be underrated.

The meteorologist will appreciate that every coastline constitutes a boundary with a temperature discontinuity across it. Where the gradients of temperature are greatest, the local weather problems are usually greatest, particularly if there are mountain ranges close to the coast. Land and sea breezes may be of major importance to act as triggering mechanisms at such times when the atmosphere has built up to a critical state.

The importance of such specialized problems to shipping cannot be over-emphasized. The onset of local winds, particularly of katabatic winds, may be very rapid. An occasion is recalled when, upon entering Villefranche Harbor (near Nice, France) in very pleasant weather under clear skies, good visibility, and winds of no more than ten knots, a mistral struck without any prior warning. Within 15 minutes, the wind was at full gale force in excess of 40 knots. Waves did not have time to form in the accepted sense. The crests were torn off the initial wavelets, giving the impression of a giant drawing a white sheet over the surface of the sea. Spray soon filled the air and stung the face with solid salt particles (the evaporation rate in such circumstances is very high). Two vessels dragged anchor and went aground, powerless to do anything to save themselves.

In these circumstances, the most dangerous zone is often the first 20-25 miles seawards from the coast, although it can vary with circumstances. Many small ships try to stay within this distance so that they can run for the shelter of port at the first signs of danger. It would be wrong to suggest that they should not do this, but they should appreciate that this is not necessarily the best course of action, particularly if they are caught and have a long way to get to port sailing in the teeth of the wind. The seas are steep with exceptionally short wave lengths in these cold katabatic winds having a limited fetch. In high latitudes, the dangers of ice accretion are very great if the winds are at sub-zero temperatures and flowing off an ice-bound surface. It could well be better to run before the wind and get further to seaward where the seas, although higher, will be longer and less steep and the air temperatures several degrees higher as a result of a long sea passage.

It is difficult to provide adequate forecasting services for such events, but national meteorological services need to have the expert local knowledge and the communication facilities to provide the local information to small vessels, particularly by voice procedures. The need for the latter is strongly stressed for waters prone to katabatic wind flow, and the advice to seamen is to stay tuned in to receive the local meteorological weather bulletin at all times. In Chapter 15 we will consider some techniques used to detect and monitor fronts.

CHAPTER

15

MONITORING COLD AIR OUTBREAKS OVER THE OCEAN

15.1 Introduction. Cold air outbreaks, as we have seen, often create very hazardous conditions for the mariner, and it is important not only to detect the presence of these cold fronts, but to track and predict their movement. This is sometimes difficult. In this chapter, we will examine techniques that were successfully used in the South Atlantic to detect and track cold air outbreaks from Antarctica to the southwest coast of South Africa. Similarly, the techniques will be examined as applied to outbreaks moving from Alaska to Vancouver Island, Canada.

15.2 A plotting technique for detecting and monitoring cold air outbreaks in the South Atlantic. Since the propagation of cold air outbreaks is often directional and confined to a narrow bandwidth, it is often possible to detect and monitor the progress of the cold air by graphical technniques using barometric pressure and the dew point as the indicators. This technique was found to be a particularly valuable forecasting aid in the South Atlantic. It can be shown to also work in the Northeast Pacific under certain circumstances.

The principle is the selection of a number of stations along the mean path followed by cold air streams to the area of interest assuming an average speed of advance of the cold air boundary of 25-30 knots. Obviously, such an assumption is a very general one to make, but polar fronts moving in deep cold air masses in the rear of depressions often have unimpeded progress over hundreds of miles of open ocean along a great circle path before being appreciably modified or arrested in lower latitudes. This technique may be considered to apply to these special circumstances. The average progress each day is of the order of 600-700 miles, and it is usually possible to select good reporting stations along the route at distances of the order of 150, 300, or 600 miles so that fronts advancing at this average speed approximately arrive at selected stations at intervals of 6, 12, or 24 hours.

In the South Atlantic areas, the grid was defined to first detect antarctic outbreaks of deep polar air by means of the observations in the Grahamland Peninsula. Such outbreaks usually followed the movement of a depression into the Drake Strait between Antarctica and South America or one crossing the peninsula into the Weddell Sea area. A marked fall in dew point usually occurred at the antarctic stations, with a corresponding rise in pressure and occasionally a southerly blizzard. The cold air flooded northwards off the continent or the ice shelf aided probably by the entrainment action of the depression as it moved into Antarctica, the blizzard being caused or aided by drifting snow fields.

The progress of the cold air was then monitored by means of synoptic reports at the island stations of: (a) South Orkneys (60°35'S 45°30'W) and the Falkland Islands (51°45'S 59°00'W); (b) South Georgia (54°15'S 36°45'W); and (c) Tristan da Cunha (37°15'S 12°30'W), which were at approximately 600, 600, 1,200, and 2,000 miles, respectively, from the originating area of the outbreaks in the Weddell Sea area (see Figure 62).

The pressure and dew points at these stations were plotted four times daily on large wall graphs using the average time stagger so that the discontinuities fell approximately into vertical alignment. Southerly busters were thus tracked as they crossed the southern oceans, and it proved to be easier to do it this way than by con-

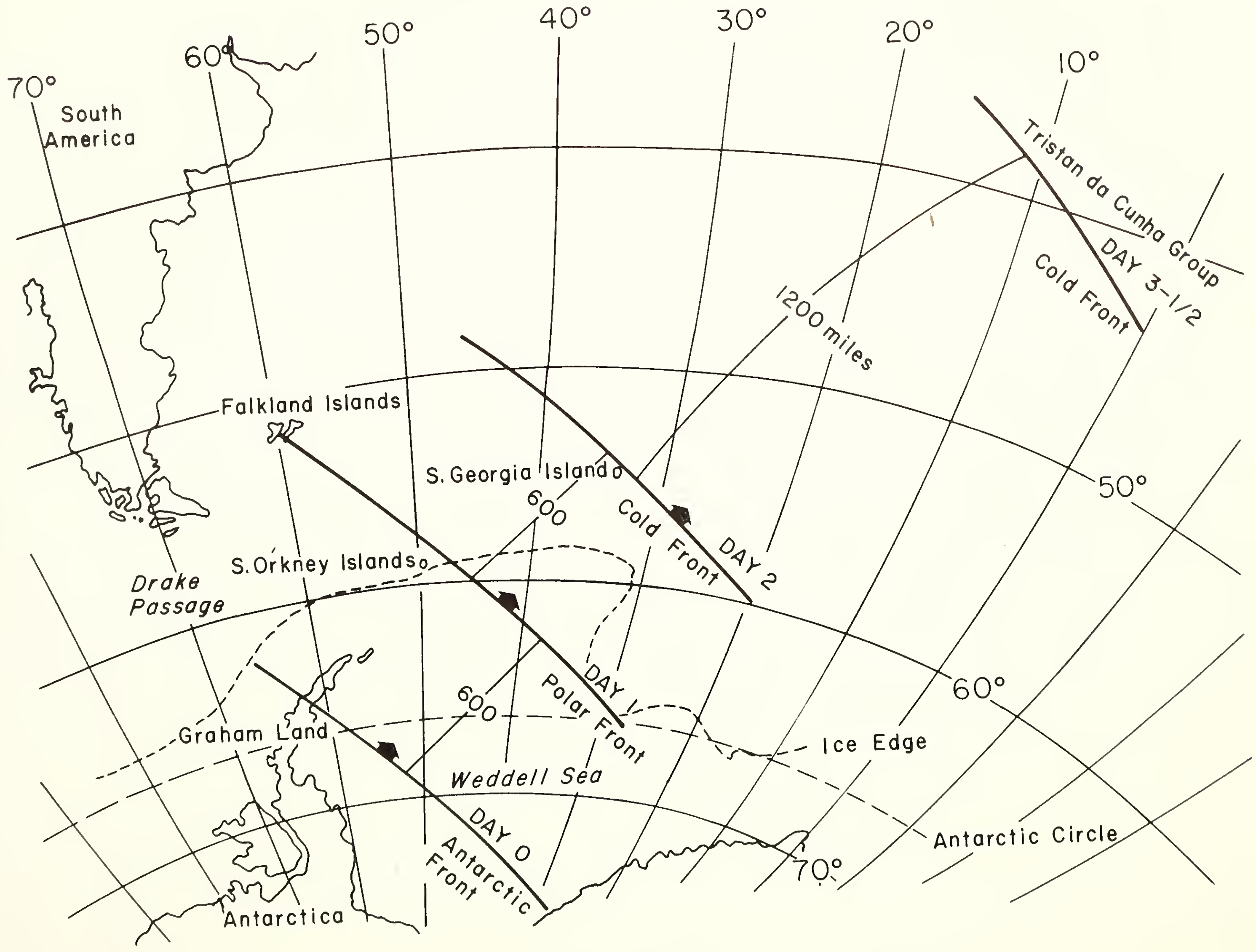

Figure 62 - Cold air outbreaks from Antarctica.

sulting a sequence of several days of synoptic charts. The latter were used as backup information, but the former technique crystallized the problem to reveal the important operational feature. An interval of approximately five days occurred between the initial outbreak and the arrival in the area south of the Cape of Good Hope where these cold air outbreaks met the contrary flowing Agulhas Current.

Meteorologists are frequently credited with the statement that it is quite impossible to forecast the weather for more than three days in advance. General agreement is accorded with this view, but there are exceptions and one is the almost unimpeded and regular progress of major polar fronts over open oceans. During the southern hemispheric winter, it was occasionally possible to follow their progresss right up into the equatorial latitudes and, periodically, until they actually crossed the equator (*i.e.*, they could occasionally be tracked for nine or ten days).

15.3 The variations in intensity of blocking anticyclones and the subtropical high pressure systems. One additional and important asset of the graphical technique developed for monitoring cold air outflows from the Antarctic Continent lies in its usefulness for indicating fluctuations of intensity (due occasionally to the displacements from the mean position) of the major anticyclonic systems. The function of the subtropical anticyclone was regarded as a blocking system to the north-south (or south-north) movement of the cold air masses. The air mass is deviated from its path and constrained to move eastward along the boundary on the poleward side of the subtropical highs until a col is encountered between two adjacent cells. The air mass can then escape into the trade-wind zone to continue its flow at surface level towards the tropics.

The result of such flow (particularly of cold air in the lower levels of the atmosphere) gives the impression of the intensification of a migratory anticyclone on a sequence of synoptic charts. Thus, cold air outbreaks from the Weddell Sea area appeared as an intensification of the antarctic anticyclone in that area.

Some complementary development occurred in the South Atlantic subtropical high pressure cell in consequence. As the antarctic anticyclone intensified or moved northward, the subtropical anticyclone appeared to weaken or retreat northward. The development and movement of depressions in the lower latitudes was also affected similarly, since they formed some distance to the north of the mean position of formation and were forced to follow a track at lower latitudes than normally. In other words, the sympathetic movements of the pressure graphs for Tristan da Cunha and South Orkneys could be interpreted as a fluctuation of the mean depression belt.

When viewed on the graphical presentation, it could be generally interpreted as an oscillation or pulsation in a semi-systematic interval pattern recurring every 15 to 19 days. Serial correlation tests using long series of pressure values to both Tristan Da Cunha or South Orkneys confirmed that such a general quasi-systematic variation existed at most times and particularly in winter. Auto-correlation tests confirmed the general inverse relationship between the two stations, expressed as a fluctuation of the mean depression path.

It proved to be a valuable forecasting tool, although not necessarily a precise one. Thus, it was not ususally possible to say whether the average value for one of the intervals would be a little greater or a little less than 17 days. Furthermore, it was not possible to predict the amplitudes of the pressure fluctuations, although generally they were of the order of 8-10 millibars at South Orkneys and somewhat less at Tristan da Cunha; but the forecaster seldom had doubts as to when he would be dealing with crest or trough situations in five or six days time.

The physical explanation for these relationships is found in the development and movement of the migratory anticyclones. Cold air accumulates by subsidence over the antarctic plateaus or ice shelves, and it is periodically displaced and escapes in the wake of invading depressions. This occurs at more or less regular intervals of time and very much in preferred areas as an indirect result of the steering effects of the well-formed subtropical anticyclones. Cold air outbreaks from polar regions in the Southern Hemisphere are in effect quasi-periodic. This creates the impression of semi-regular oscillations of the order of 13-17 days in the pressure graphs of the island antarctic stations. There is an induced or sympathetic opposite intensification and decay of the subtropical anticyclone in the South Atlantic. It was possible to identify these oscillations on the wall graphs by eye without difficulty and to predict when the next crest or trough would occur in either graph to within a day or so. This could be done about a week ahead of the occurrence.

The value of such a prediction is immediately apparent. One way of viewing the sympathetic oscillation is to consider it as a north-south oscillation of the depression belt. When pressures were high (*i.e.,* when a crest was present) in the antarctic graphs, pressures were lowest in the Tristan da Cunha region (*i.e.,* the depression centers had a more northerly track), and the waters to the south of the Cape of Good Hope were relatively more stormy.

It can well be asked how regular were these pulsations of pressure? The answer is that in winter, variations seemed sufficiently regular to be of operational use, although the waves had varying degrees of amplitude. Very occasionally, a depression center would form to the north of Tristan de Cunha and then the pressure graphs of Tristan da Cunha and South Orkneys appeared to pulsate in sympathy, rising and falling together. But this was a rare occurrence and more generally the inverse relationships held.

With experience it became possible to formulate certain empirical rules. Thus, if the pressure at South Orkneys exceeded 1005 millibars (this was regarded as abnormally high -the mean pressure being of the order of 990 millibars) pressure at Tristan da Cunha fell and approached 1000 millibars. This was a certain indication that depression centers were constrained to follow a more northerly track than average, and, in consequence, the waters to the south of the Cape would be particularly stormy some 36 to 48 hours later.

Many meteorologists unfamiliar with such techniques and trained only to forecast developments from synoptic charts will be unhappy with the method and particularly with the claim that it permitted a five-day forecast. It must be admitted that much of the success of the graphical technique, which was developed for forecasting in the South Atlantic, was due to the general absence of blocking anticyclones in the depression belt. The anticyclones that were present in the westerlies were most often truly migratory and really represented a cold air mass traversing the depression belt from the frozen Antarctic Continent to join one or other of the trade wind streams on the eastern side of a subtropical high.

If a blocking situation truly developed in the South Atlantic, the graphical technique for forecasting the arrival of southerly busters broke down. But such occurrences were rare, and it was generally not difficult to recognize this at a very early stage of formation and make allowances accordingly. The point is made that the circumstances were unusual and perhaps unique and that the method might not work elsewhere. Nevertheless, it is worthwhile to investigate the possibilities in the North Pacific where the ocean is broad and the subtropical high pressure cells are well-defined, although not to the same degree as those found in the South Atlantic or South Pacific.

15.4 A plotting technique for detecting and monitoring cold air outbreaks in the North Pacific. The width of the ocean in the North Pacific suggests that possibilities exist for employing similar techniques to those developed for the South Atlantic, but for detecting cold air outbreaks from the arctic region and monitoring their progress to low latitudes in like fashion. It is a very much more difficult problem than the one described for the South Atlantic for a number of reasons.

The main one is that the mean track followed by depressions across the Pacific is not such a clearly defined lane. The subtropical high pressure cells of the Southern Hemisphere vary little in position and intensity from day to day. The subtropical high in the North Pacific does not compare in respect to persistance of position and intensity with the subtropical high in the South Pacific, which influences and steers the depressions in the same general direction at all times. With the Andes Barrier playing a blocking role to the east and the frigid Antarctic Continent to the south, depressions forming in the South Pacific are constrained to follow the channel southeastwards, toward the Drake Strait and into the Weddell Sea area. It is only when they cross the Grahamland Peninsula and the centers are east of the Andes Barrier that their day-by-day movement and position becomes more erratic. Even so, most of them finally cross the coastline or sea ice shelf somewhere in the Weddell Sea area, and a great number of them result in the entrainment of cold air from off the Antarctic Continent and the ice shelf as they do so.

It may be argued that this emergence of cold air mass from the icy surface is mainly due to an accumulation of an air mass, formed by radiation from the snow covered surface and that the passage of a depression is only the trigger mechanism to set it in motion. This argument is largely an academic one and will not be pursued. The important point in that a very large number of cold air outbreaks originate from the Weddell Sea area with some directional outflow aided by the mountainous backbone of Grahamland. Similarly, cold air outflows take place in the winter months from the Bering Sea ice shelf and from Alaska.

15.5 The subtropical anticyclone. Although the North Pacific subtropical anticyclone shows a higher degree of permanence than other similar cells in the Northern Hemisphere, it is not always one well-defined high pressure cell, and at certain periods of the year it is possible to find two anticyclonic cells in the ocean separated by a weak col. The two cells behave somewhat independently, and one consequence is that the centers of some depressions approaching the Gulf of Alaska from the west pass north of the Aleutian chain of islands and either fill up in the Bering Sea or cross the coastline of Alaska. However, this encourages the view that it is possible to draw a parallel with the Weddell Sea and to look for some emergence of polar fronts from the Bering Sea to be detected and monitored by the observations at St. Paul Island and at Cold Bay (see Figure 63).

Blocking anticyclones in the belt of westerlies occur with much greater frequency in the North Pacific than they do in the southern oceans, and this is an additional reason why depressions do not follow clearly defined routes with any regularity.

15.6 The frozen land masses and ice shelves of the North Pacific. Some similarity exists between the Bering Sea and the Weddell Seas in that both are largely ice-filled sea areas in winter. The former becomes ice free in summer, but not so for the latter. Although Alaska and western Canada are mountainous in much the same fashion as Antarctica, the similarity is not great, for there is no Drake Strait through which depressions can pass. In addition, many of the mountain ranges in Alaska are orientated east-west presenting barriers at right angles to north-south flow.

Flows which cross the Aleutian Chain into the Bering Sea seldom recross the panhandle into the Gulf of Alaska. Those which arrive in the Gulf of Alaska (particularly in winter) often find their eastward progress arrested by the blocking anticyclones anchored to the frozen land masses to the east and north. They cannot readily escape so they slow down, often intensify, and then fill up in the same general area.

There is no close similarity with the Weddell Sea area in the summer months, for the land masses of Alaska and Canada become unfrozen and occasionally hot. Depressions can pass inland more readily, and when they do so, they do not entrain a cold air mass from the continent over the Gulf of Alaska. The circumstances do not vary greatly from winter to summer in the Weddell Sea area.

15.7 The main depression tracks. Thus, the problem is not clearly similar. Even so, those depressions following easterly tracks across the North Pacific often cross frozen coastlines during the winter months thereby causing cold air from the frigid interiors of the continent to move southwards over the oceans. Hence, any grid system which can assist with the detection and tracking of such air masses will be a useful aid to the marine forecaster. As with the South Atlantic, it will be seen that the graphical technique can on occasion be a valuable aid to synoptic sequences since it helps to ensure that arctic and polar fronts embedded in the cold air masses are not overlooked. Furthermore, it gives a broad picture of the pressure fluctuations over a period of several days indicating trends or variations of intensity in the blocking anticyclones whether these be anchored over the land or the sea. Such variations largely determine the tracks air masses must follow across the oceans. The techniques, therefore, constitutes a valuable aid for an extended range outlook, which would be particularly useful for ship routing on northern routes.

15.8 The significant station reports for a grid. The first stage in developing a similar technique for the North Pacific is to study the topography and the location of the main reporting stations on the Alaskan Peninsula (see Figure 63). The ice-bound land surface and frozen sea boundary is sensibly defined by following the 60th parallel across the Bering Sea to Cape Avina. From Cape Avina the frozen boundary may be considered to arc to King Salmon, thence across the Alaskan panhandle to the entrance to Cook Inlet, thence eastwards following the arc of the Alaskan coastline to Yakutat, down the archipelago to Langara and finally to Vancouver Island.

One hundred and fifty miles seaward of this demarcation line of frozen land and sea mass (in winter) a

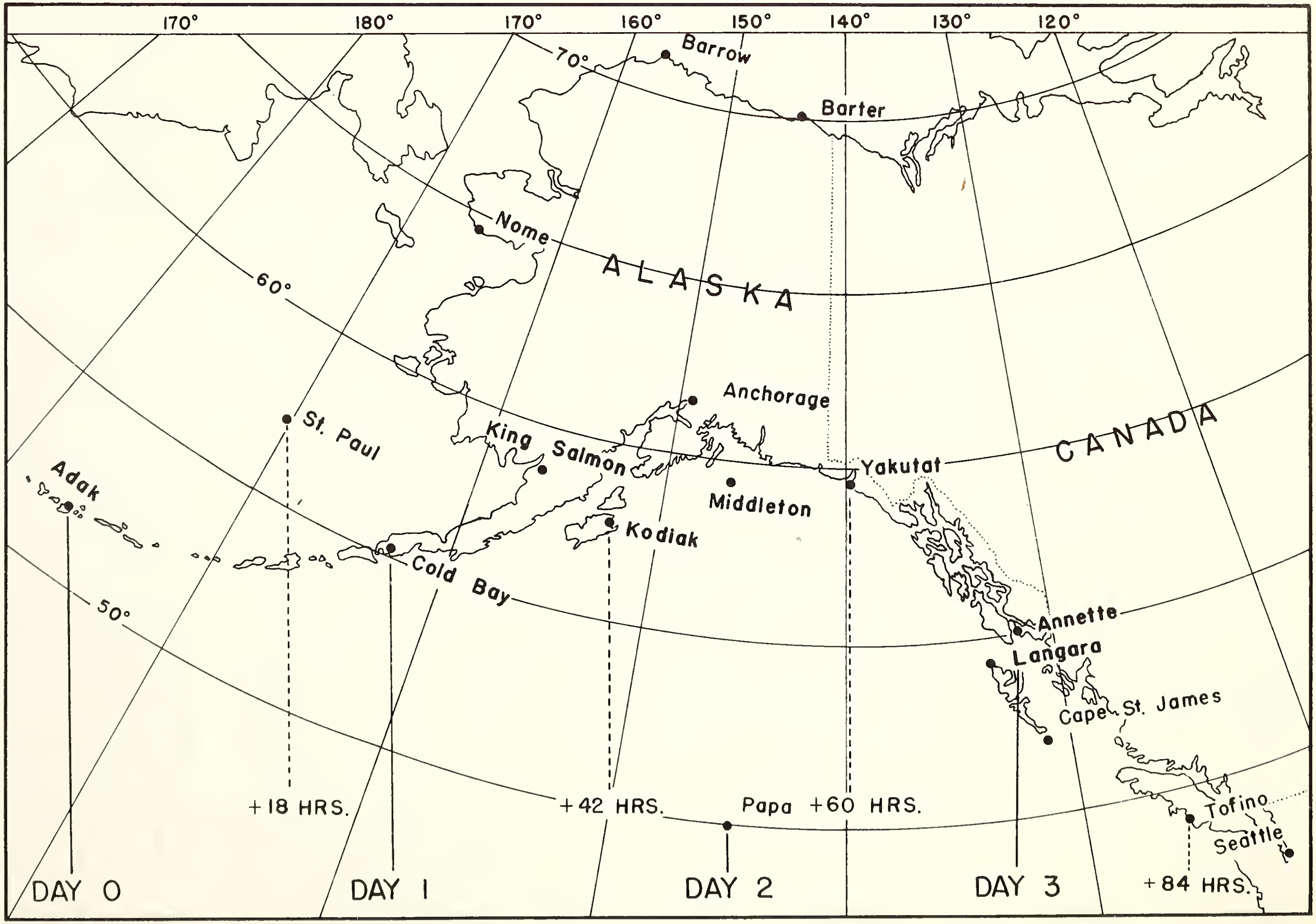

Figure 63 - Chart showing stations and the time staggers used to allow for mean movement of lows and fronts.

parallel and outer boundary line can be drawn (dotted in figure) to pass through (or close by) the stations of St. Paul, Cold Bay, Kodiak Island, Middleton Island, Langara, Cape St. James, and Tofino on Vancouver Island. The array of automatic reporting buoys which has now been deployed 200 miles from the Alaskan and Canadian shores reinforces this outer indicator line making it even more effective for detecting changes in air mass. Surface synoptic reports from these stations (or the buoys) can first be used to determine the location where depressions will cross the coastline.

The effects of depressions progressing in a generally eastward direction will first be registered by pressure falls at Adak and then successively at Cold Bay (or St. Paul), Kodiak, Yakutat, Langara, and Tofino. The sequence of synoptic events at the buoys and Ocean Station PAPA also helps to monitor the progress of depressions and the analyst should have few difficulties in pinpointing the area on the indicator boundary line where the depression center crosses the outer line and passes into the interior or over the ice shelf. From this he can determine when the entrainment process begins. It is convenient to divide up the frozen boundary line into two main zones, each of which can be further subdivided into two subzones:

Zone (1) Adak to Kodiak
- (a) between Adak and Cold Bay;
- (b) Cold Bay to Kodiak;

Zone (2) Kodiak to Cape St. James
- (a) Kodiak to Yakutat;
- (b) Yakutat to Langara or Cape St. James.

In Zone (1) the arctic air mass will either have originated over Siberia or from the ice shelf in the Bering Sea ice shelf and in Zone (2) from off Alaska or northwestern Canada. The monitoring of air masses in this way should form a normal part of the forecasting task for the marine areas and may be aided by plotting some or all of the pressure and temperature values of the stations Adak, St. Paul, Cold Bay, Kodiak, PAPA, Yakutat, Langara, and Tofino on a wall graph allowing a stagger so that minimum pressures fall approximately into vertical alignment. The suggested stagger based on an average rate of progression of 20 knots toward the east-northeast direction is Adak (zero), St. Paul (18 hours), Cold Bay (24 hours), Kodiak (42 hours), PAPA (54 hours), Yakutat (60 hours), Langara (72 hours), and Tofino (84 hours). It is also desirable to include Middleton Island (48 hours) and Cape St. James (72 hours) since reports from the primary stations are occasionally late or are missed.

Example. The method is illustrated by a weather series for the Gulf of Alaska from 15-22 February 1975. Figure 63 shows a chart of the area considered, the indicator stations used in the analysis, and the stagger system employed in following the passages of lows and fronts across the area. On the graphs plotted in Figure 64, pressures and temperatures are plotted for nine stations: Adak, St. Paul, Cold Bay, Kodiak, Ocean Station PAPA, Yakutat, Langara, Cape St. James, and Tofino, -each covering a 3½ day period for the stations. The temperature and dew point scales are plotted inversely to show more clearly the tendency corresponding to the atmospheric pressure. The plotted weather observations are shown in Figure 65. The observations in both Figures 64 and 65 are staggered so that the discontinuities caused by moving fronts (or lows) tend to fall into vertical alignment. The hours of stagger employed are as given above and as indicated in Figures 63 and 64.

For further interpretation of the observations, synoptic sequences with four surface charts per day are given in Figures 66 through 72. This sequence was also used in illustration of the spectral diagrams discussed in-Chapter 12. Many of the observations have been omitted in order to preserve clarity, and the station model shown in Figure 9 is used for the ship observations. (Values of effective wind are not shown.)

The movement of two depressions over the Gulf of Alaska from west to east is involved and is clearly revealed in the pressure graphs of Adak, Cold Bay, and Yakutat. The centers crossed the Gulf of Alaska south of the Aleutian Chain. Hence, their effect was hardly noticeable in the pressure trace for St. Paul, which is to be expected. The centers finally moved inland between Anchorage and Yakutat. To employ the technique to the

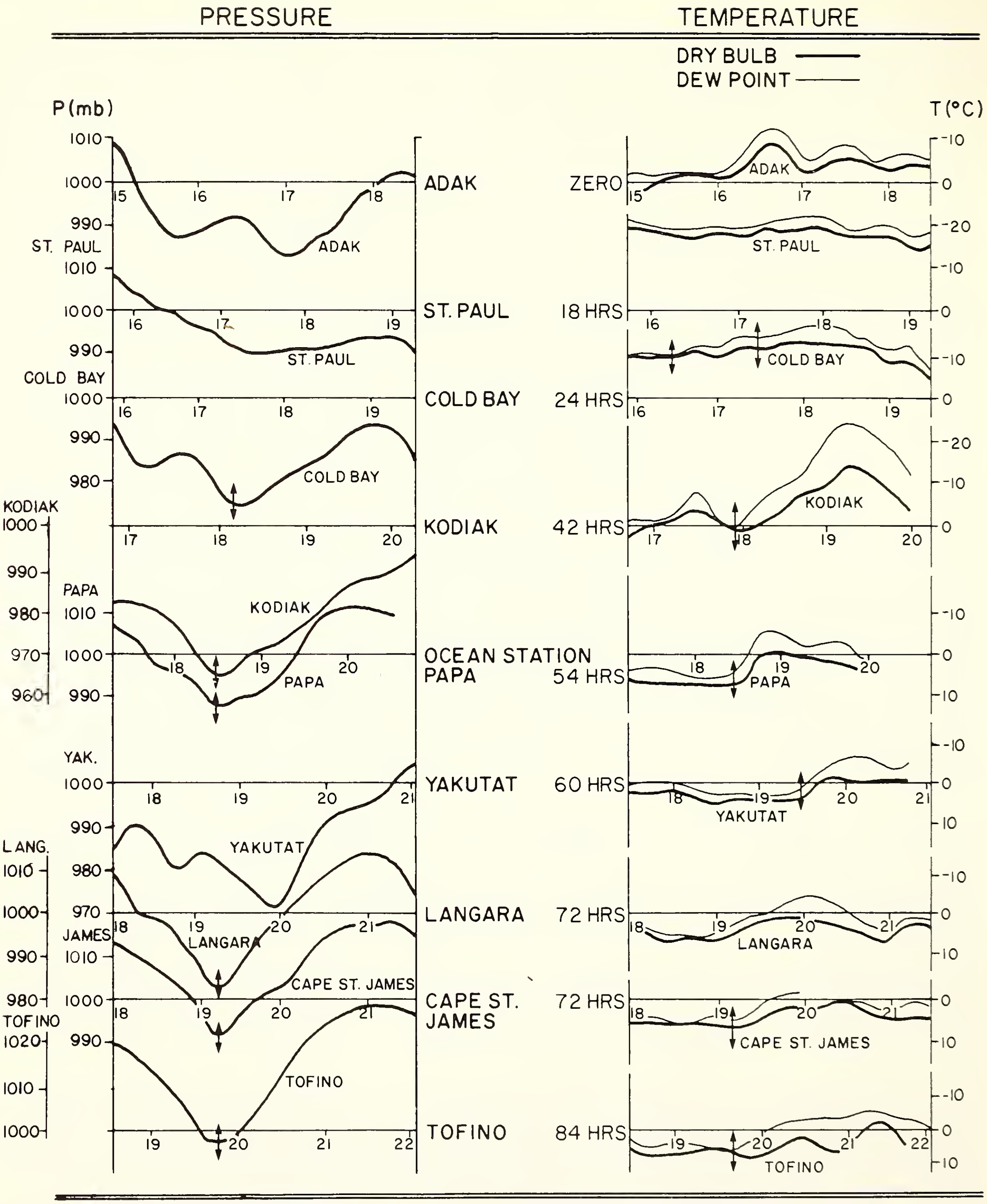

Figure 64 - Staggered graphs of pressure, temperature, and dew point for 15-22 February 1975.

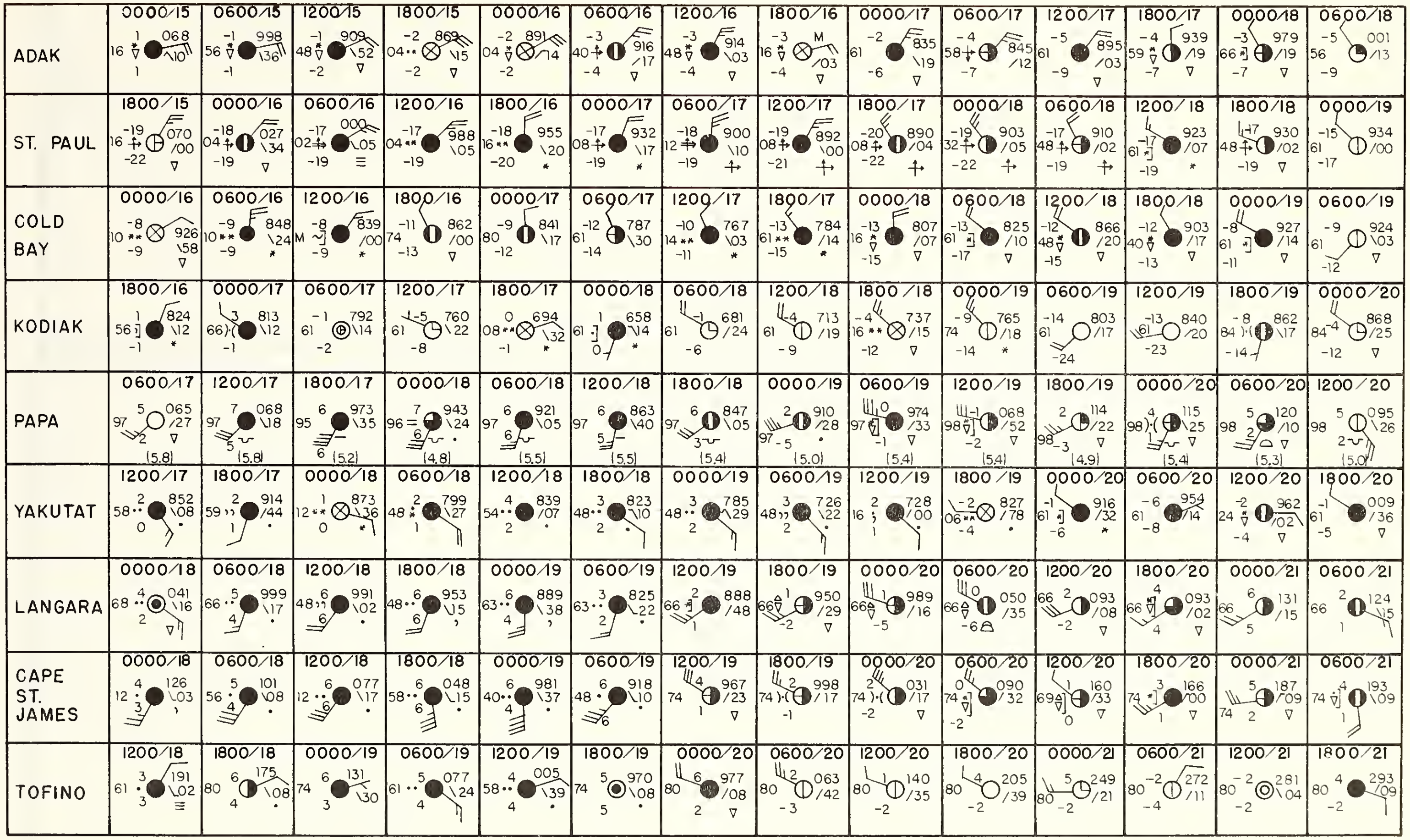

Figure 65 - Plotted weather observations, 15-21 February 1975 (staggered dates).

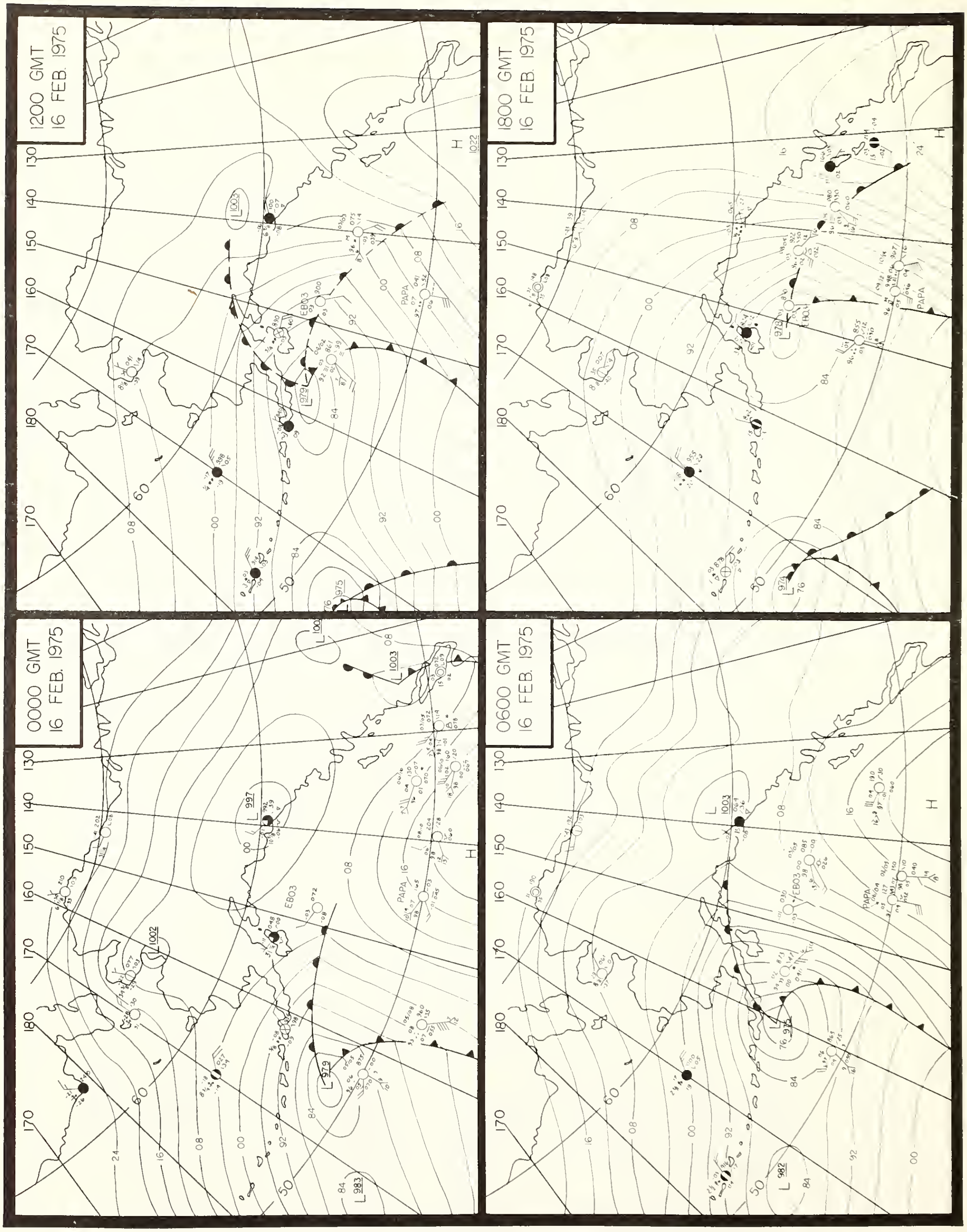

Figure 66 - Synoptic sequences for 16 February 1975.

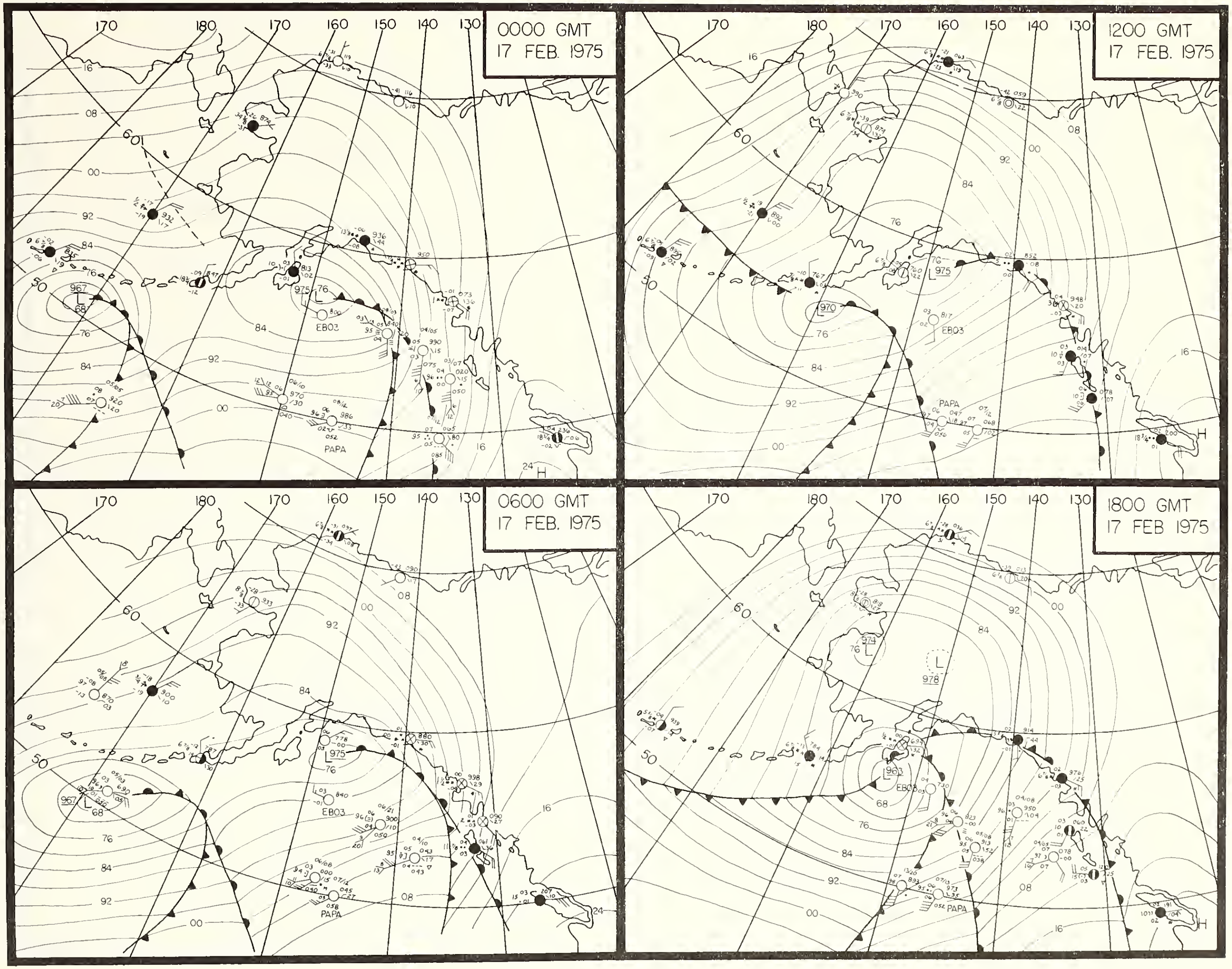

Figure 67 - Synoptic sequences for 17 February 1975.

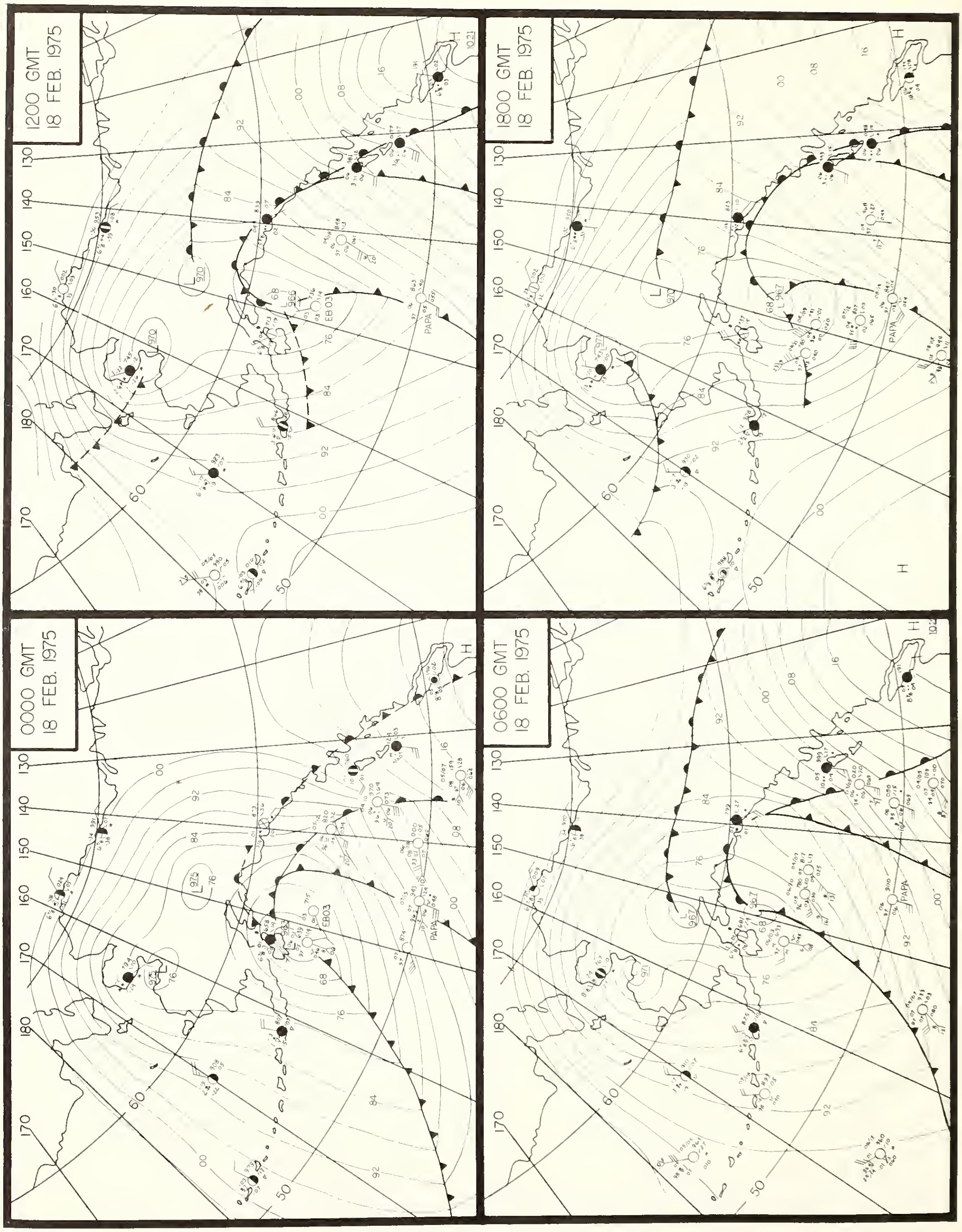

Figure 68 - Synoptic sequences for 18 February 1975.

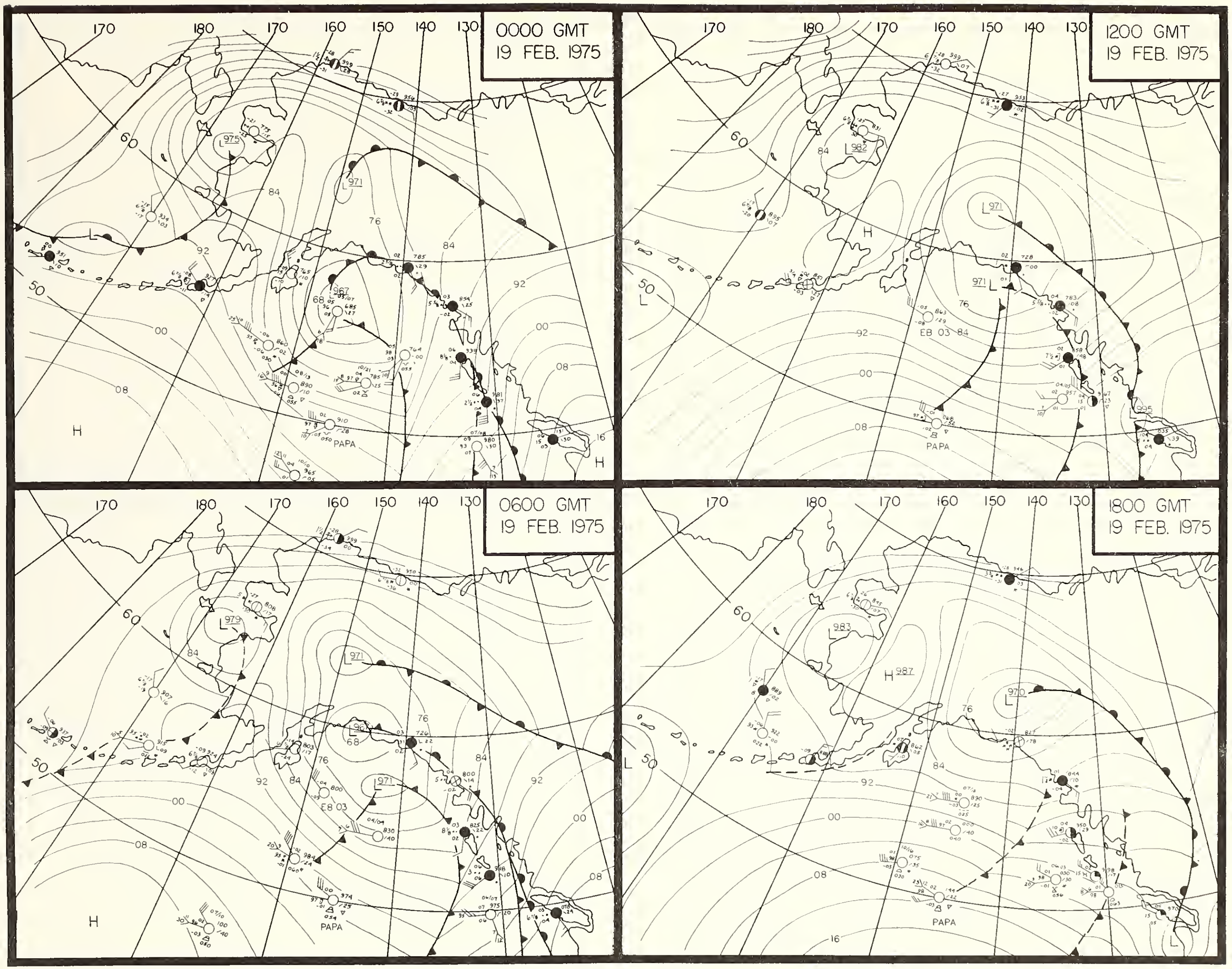

Figure 69 - Synoptic sequences for 19 February 1975.

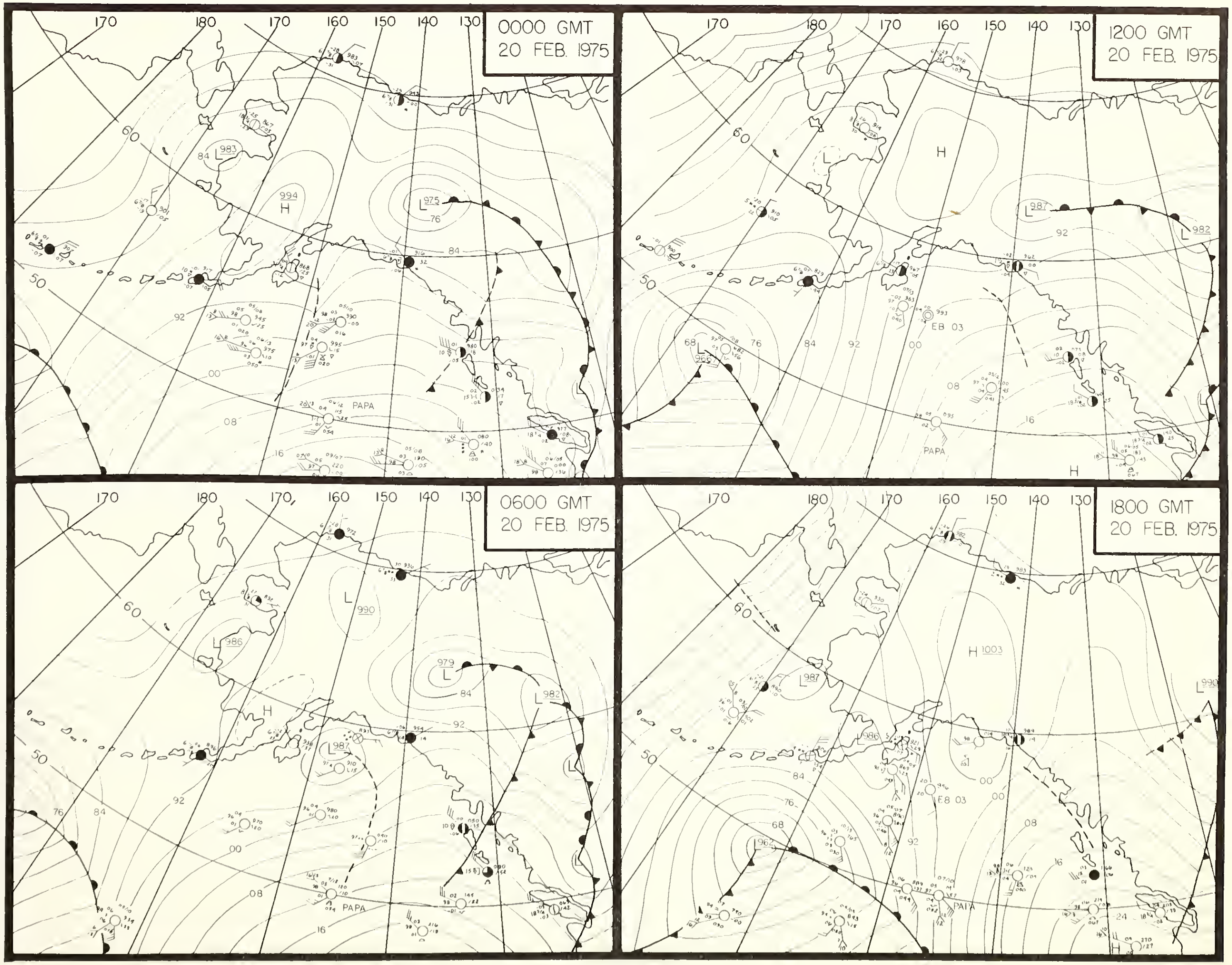

Figure 70 - Synoptic sequences for 20 February 1975.

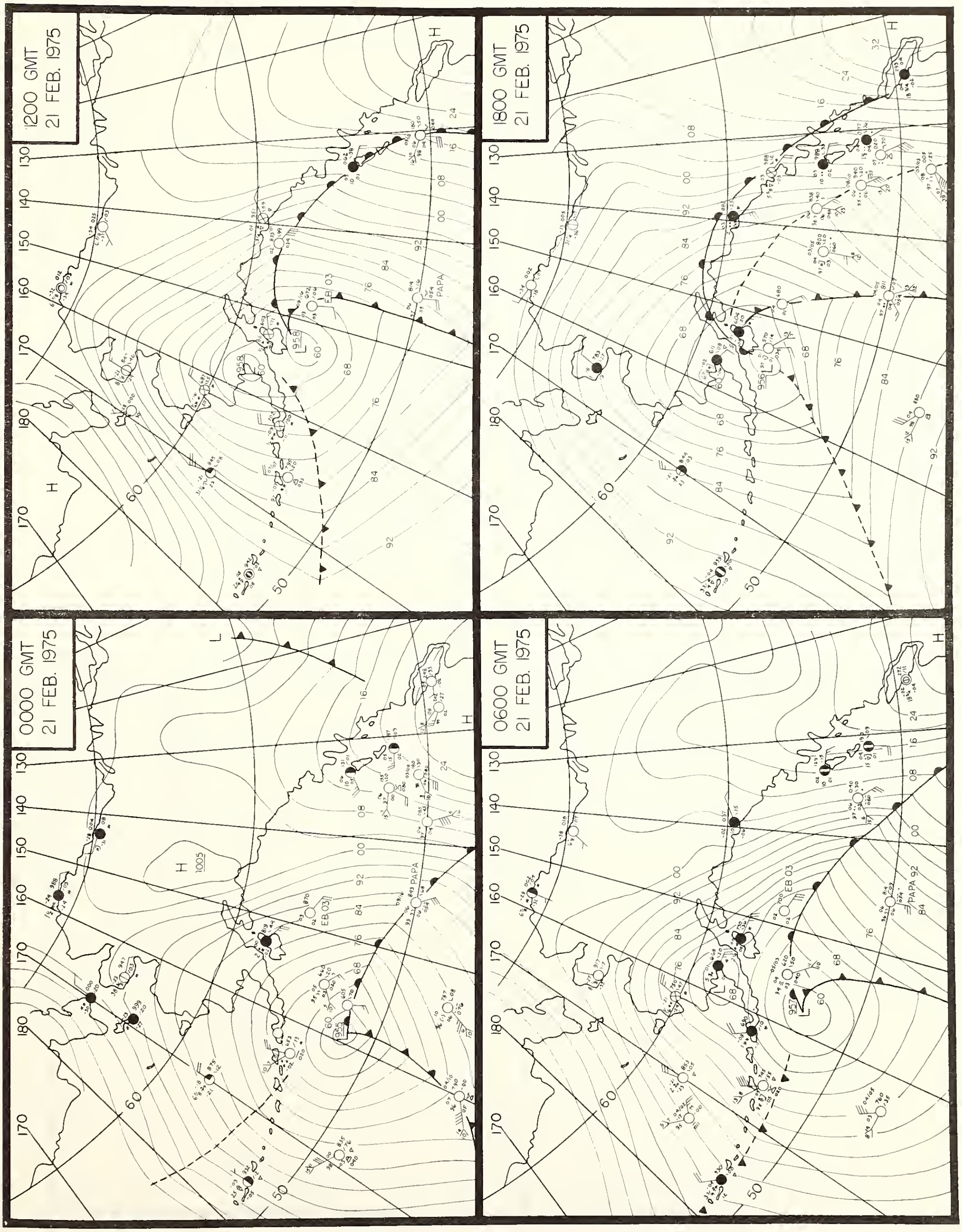

Figure 71 - Synoptic sequences for 21 February 1975.

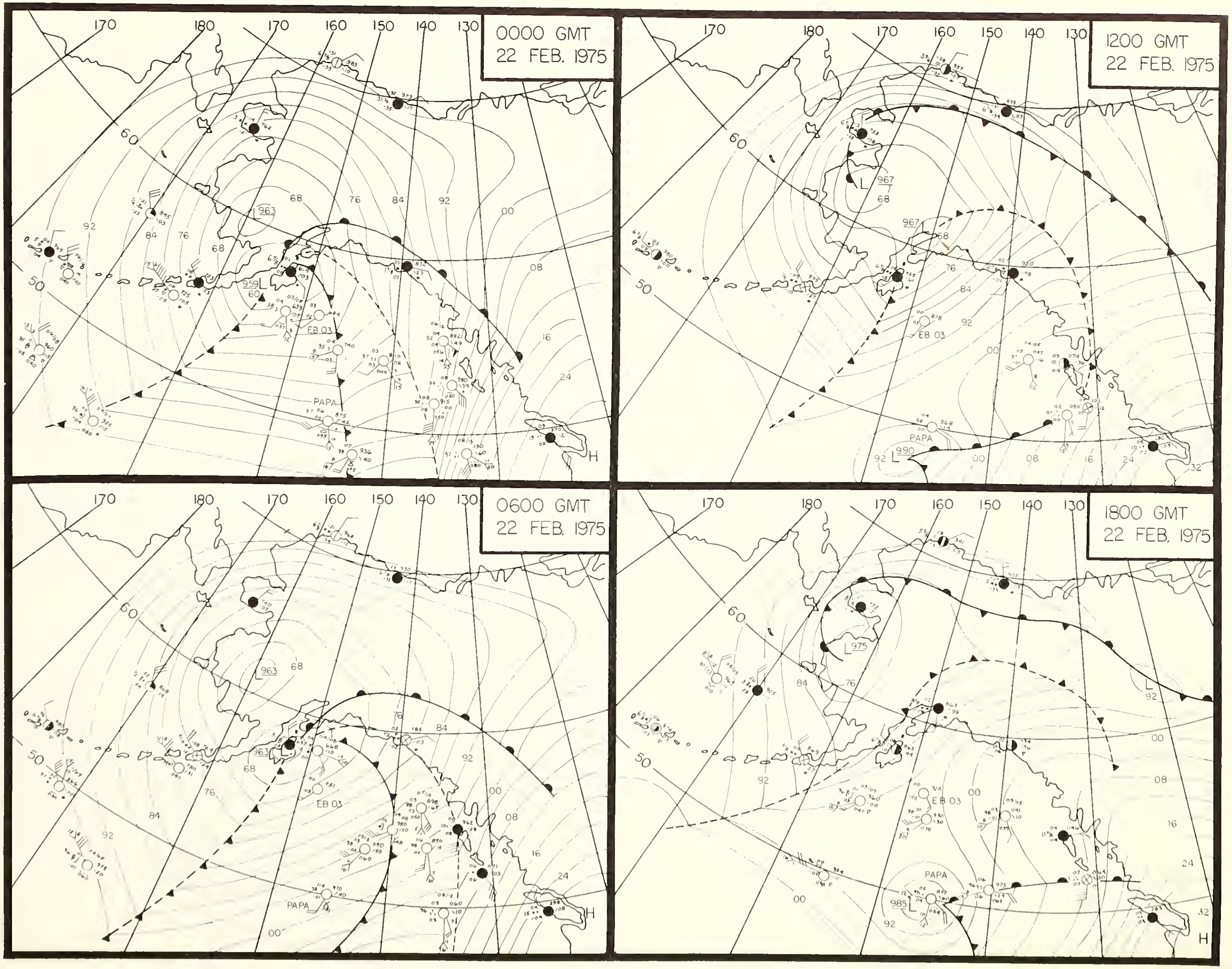

Figure 72 - Synoptic sequences for 22 February 1975.

fullest advantage, a distinction between the effects of centers and the effects of fronts or air mass changes must be attempted while interpreting the graphs. This is clearly illustrated in the graphs concerning Kodiak. The pressure graph principally indicates the passage of two centers, but the temperature graphs show in addition the egress of a limited cold air mass on the 17th followed by the main cold air outbreak commencing at 0000Z on the 18th. The arrival of this polar front at PAPA at 1800Z on 18 February is clearly seen as is also its subsequent arrival at Cape St. James at 0600Z on 19 February and Tofino at 1800Z on 19 February.

This polar front continued its uninterrupted passage southward over British Columbia and reached the Puget Sound area early on 20 February. It was destructive to shipping off the coast and in the inland waterways. The front could only be detected with difficulty on the satellite images of 19 February because relatively little cloud was associated with it, and an inexperienced forecaster could easily have overlooked it. The severity of the squall associated with the front and the sea and swell generated in its wake was considerable; traffic in the Seattle area was brought to a standstill in a spectacular blizzard.

15.9 Semi-systmatic variations in the pressure and temperature graphs at stations in northern Alaska. In the first part of this chapter, a plotting technique was described for detecting cold air outbreaks across the South Atlantic and also how the intensity of fronts and lows could be monitored from a study of the semi-systematic variations in pressure of the order of 15 to 19 days in the antarctic stations and at Tristan da Cunha. These were sufficiently regular and of adequate amplitude to enable a forecast to be made. On many occasions, an estimate was possible of the position of the next trough or crest in the pressure graph several days in advance of the occurrence, thus enabling the forecaster to make a general prediction of whether a particular two-to-three day period would be more stormy or less stormy than usual. When considering the subsequent synoptic development, he could then modulate his forecast of severity accordingly. The physical interpretations placed on these pressure fluctuations is that the pressure in high pressure cells in high latitudes builds as a result of subsidence until a certain critical stage is reached. At a certain stage of development the cold air mass starts to flow southwards as a cold air outbreak, the interval between such outbreaks being sensibly regular. The inverse correspondence with the sub-tropical highs is a direct result of transfer of the air mass from high to middle and low latitudes.

An examination of the pressure graphs at station on the north slope of Alaska (*i.e.,* Barter Island, Barrow, and Nome) indicate that similar semi-systematic variations of pressure of approximately the same periods exist.

These semi-systematic fluctuations are not as clearly defined as in the South Atlantic and are probably less reliable as a forecasting tool, and some further investigation is desirable to see the limits of their use. A short sequence of pressure graphs for the stations is shown plotted in Figure 73 with crests and troughs indicated. Further research is necessary to determine if there are corresponding sympathetic variations in the North Pacific sub-tropical high. If such a relationship could be determined, it might well be a valuable indicator of the movement of centers into and across the Gulf of Alaska.

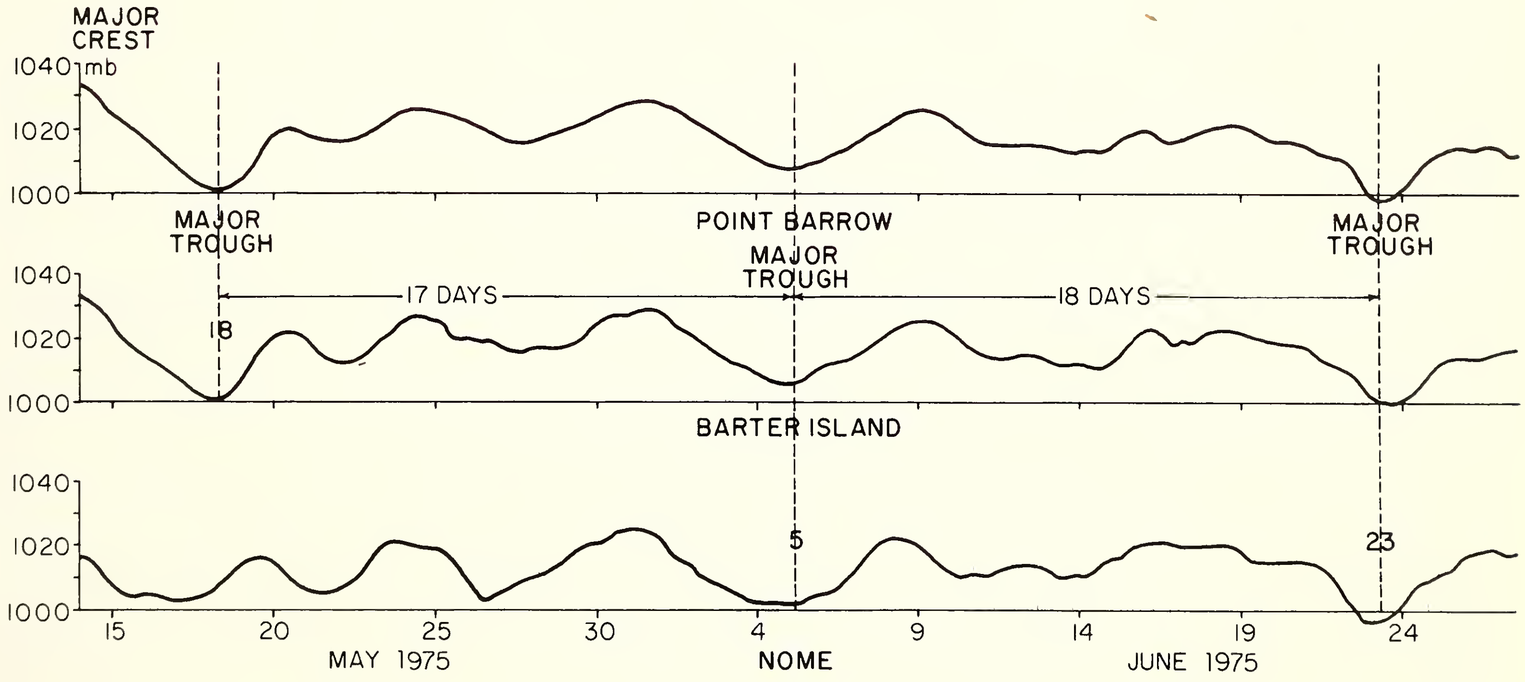

Figure 73 - Pressure graphs for Point Barrow, Barter Island, and Nome, Alaska.

CHAPTER

16

ENVIRONMENTAL SERVICES TO MARINERS

16.1 Introduction. The mariner himself can make some contribution toward improving marine weather forecasts, warnings, and ocean advisories,and in this chapter the question of how this can be done by closer rapport with shore-side organizations will be discussed. The seaman's contribution to the system will always be great if he sends regular weather reports. This has generally been so, and the quality and quantity of data received daily from the world's oceans, largely on a voluntary basis, deserves nothing but high praise. The seaman is by tradition weather conscious, and he takes pride in the reports he sends from sea. The standard of reporting is often truly professional, and this applies particularly to the estimations of sea and swell, which is a skill developed only by long practice. Sea and swell forecasting depends heavily on such reports.

In return the seaman can expect to receive gale and storm warning services, which are particularly valuable in semi-closed seas and coastal waters where the ship is constrained to maneuver within limits, and bad weather always presents hazards to safe navigation. These services, provided by national weather services for shipping of all nations, vary in quality and extent according to locality and the resources of the nations that provide them. Encouraged and guided by the World Meteorological Organization, they are generally adequate, but there must be many nations in the world that are radically revising their ideas on the problems of marine services with the introduction of the 200 mile zone of responsibility.

In the open oceans, the services are less satisfactory. The seaman has always been at some disadvantage because he can seldom gain immediate publicity to complain if he receives poor service. A complaint which is stale seldom receives the same attention as one made immediately. The excuse is often advanced in meteorological circles that national weather services could provide better services if seamen would state precisely what it is they require. Those who argue thus seldom appreciate that needs are individual, and there is a wide range of user requirements and an even wider capability to receive advice and information. To be most effective, services need to be tailored to the individual ship. There will be many who will deduce from this that national weather service should not be involved and the matter be left to commercial enterprises. This is not necessarily so, and national weather services should be geared to provide data and advice to a ship at sea in response to telephone inquiries in precisely the same way as they answer various queries from farmers on matters of agricultural importance and from aircraft pilots in respect to flight conditions. Satellite communications have improved the possibilities considerably for such telephonic communication.

The degree to which ships can help themselves varies enormously with the size and class of vessel and the number of crew available for the tasks. On aircraft carriers the landing and take-off area is highly exposed, and this results in greater weather hazards from poor visibility, high winds, sea and swell, and so on. Hence, the aircraft carrier needs its own highly efficient specialized meteorological organization, closely linked and geared by numerous communication channels to national networks.

There is a whole range of cargo ships and passenger ships that is becoming increasingly automated, resulting in reductions in numbers of crew and the consequent availability of officers for preparing and dispatching reports. Many cargo ships are giving way to tug-barge type operation engaging minimal numbers of men and relying almost entirely on voice procedures for communications with shore. The standard type of ship's weather report is looking more and more out-moded and less well-suited to ships, as radio operators with

Morse experience become fewer.

At the extreme end of the spectrum are yachtsmen and small boat fishermen with a multitude of practical tasks to attend to, making it extremely difficult, if not impossible, to conform to routine procedures such as sending and receiving advices at set times by specified communication channels. With all good will, small ships cannot conform. They willingly report the weather when they can, but the computer networks are not geared to receive their contribution or take account of them in the national networks however significant the information may be. This is a cause of much dissatisfaction with present day services.

The most important limiting factor to all weather services to seamen has always been and remains the quality and nature of the communication channels available. A very large number of channels carry or relay weather data and information, but many ships, particularly the small craft who need them most, cannot receive the advices they would like either because of expense or interference in poor quality radios or inadequate manpower.

16.2 Specialized requirements of users of marine forecasts. More attention is being focused on this problem now that man is attempting to exploit the continental shelves, particularly in the search for oil. The oil companies are very well aware that offshore engineering constructions must be of sufficient strength to withstand the most extreme buffets which the sea is capable of delivering. On many continental shelves, such as the North Sea and the Gulf of Alaska, the weather factors are extremely important and the structures must be correspondingly robust. But it should not be forgotten that the structures themselves need a fleet of small craft to service and supply them and that these are equally vulnerable to weather hazards. In the ultimate of this spectrum, individual divers are called upon to make their contributions to the construction works, and the losses of life among them have been very heavy indeed.

16.3 Oceanographic services. The question of the heavy casualties among divers in the North Sea operations is mentioned specifically because it draws attention to the wide nature of the problem which is as much an oceanographic as a meteorological one. Generally, the smaller the ship, the more it is at the mercy of bad weather, resulting not just from winds alone, but from combinations of wind, currents, and tides. Why, therefore, should a meteorological service carry responsibility for matters that are not strictly within their specialization and for which meteorologists are not adequately trained?

Fishermen in particular have long felt that national weather services are not fully geared to their needs, and hence, of all seamen they have probably been least cooperative in providing the reports from sea on which good services depend. This is not the entire story, for fishermen are by nature independent, but there is no question that better services might be forthcoming if fishermen reported the weather more frequently and if national weather services provided knowledge of the thermal structure of the oceans to them. This information is just as important to the fisherman as the atmospheric thermal structure is to the aviator.

While communication channels between ships and shore remain generally inadequate to deal with meteorological requirements alone, it would seem questionable if a proportion of them should be reserved for oceanographic information. But it should be understood by the meteorologist that to the fishermen the marine problem is not exclusively a meteorological one. Hopefully, a number of regional marine centers will be created which can deal with the specialized question of ocean forecasting and treat oceanography and meteorology as equally important.

16.4 The limitations of pressure analysis for sea and swell forecasts. A visitor to any meteorological office will see a very large number of pressure charts displayed on the walls applicable to all levels of the atmosphere from the surface upwards. From the surface chart it is a simple matter to derive the geostrophic wind vectors which are assumed to represent the wind flow at a height of approximately 300 meters. It is the accepted assumption that this basic computer product is sufficient for maritime applications. But is it?

What happens in low latitudes where meteorologists all agree that a synoptic surface chart gives little or no indication of the surface wind field and meteorological services with responsibilities for such areas use streamline analysis to determine wind flow? At what latitude should the marine meteorologist cease to use the one technique and employ the other?

Furthermore, in the temperate latitudes the geostrophic wind vectors do not necessarily bear close relationship to the wind vectors at one, five, and ten meters and at times there is almost no relationship at all. The truth of the matter is that meteorologists assume that isobars approximate sufficiently to surface streamline flow, and there is an inherent fallacy in their computer model approach to sea and swell forecasting. This is particularly true when such models do not take into consideration the reported wind values from ships at sea.

Should not an important product of a maritime meteorological center be the wind chart at ten meters, particularly over sea areas? Furthermore, the heights of seas and the rate at which they are generated are highly dependent on the velocity vectors at the sea surface level. But there the task is unfinished, for the vectors ought to be considered in combination with currents, tides, and wind stresses taken over a period of time. Is there not a need for certain regional centers to produce, transmit, and use such sea surface information as a routine matter?

Many national weather services provide gale warning services to shipping, long established and long accepted as meeting the need of ships. Although there is no question that these services are generally efficient and adequate, a valid question is to ask whether gale and strong wind warnings are not capable of improvement. Forecasts are based almost exclusively on geostrophic wind vectors derived from a surface pressure analysis. These are no longer the days of sail and the danger to ships stems more from the waves than the wind. How many meteorologists, when issuing a strong wind or gale warning, hesitate to give consideration to surface currents or tides and the consequent steepness of the waves and the possibilities of very broken water in coastal areas? The answer is that very few do because they have never been trained to do so.

16.5 Weather routing. In many countries and in particular the United States, weather routing is undertaken by private organizations, who charge fees for their services. In some European countries, notably the Netherlands and Great Britain, weather routing is carried out by the national weather services, but again charges are made. It is not the intention here to compare the relative merits of the respective national practices in this regard except to say that both are entirely dependent on the international networks on which routing forecasts are based, and private organizations could not possibly succeed if they were required to buy their data. The importance of all weather briefing is the personalized service and particularly so in shipping forecasts which should take into account ship characteristics. There are many who believe that better service to the individual results from private enterprise and that once government control is exercised, the services quickly become impersonal and inefficient. This need not necessarily be so as the weather routing as experienced in European countries and for naval vessels has shown. However, this is a controversial political issue which will not be pursued.

Of far greater importance are the questions: "Should not shipping companies be prepared to contribute more if they derive financial gain from weather services directly or indirectly? And, how much routing should be undertaken by the master of the ship? Most shipping companies are not fully aware of the major impact on services which has resulted from the withdrawal of a number of weather ships by governments or the effects of their own actions by reductions in crew numbers and in particular radio operators. The data services from the oceans is in some danger and services will probably deteriorate further, particularly if more weather ships are withdrawn. Successful forecasts and successful routing are entirely dependent on good data inputs. This is not altogether an issue of operating for profit; national weather services should have some obligation and responsibility for safety of life in the open oceans and, particularly, within their coastal waters out to the 200 mile limit. Without reports from these zones or the open oceans there can be no worthwhile services, and any assumption that it is now well cared for by the present satellite surveillance or that such methods will ultimately be an adequate substitute are pathetically illogical. Satellites can only partially undertake the task.

The launching of the Seasat* satellites with the capability to make certain measurements over the sea surface will indeed be a major step forward, but to date these vehicles are unproven and much research and development will be necessary before they will be effective in the data collection system. Just how many of them will be necessary to provide a truly synoptic service remains to be determined and this may well take more than one decade.

**Ed. note: See editor's note in Chapter 2 about Seasat.*

16.6 Some suggestions for improving services to shipping. Since limited finance is always the argument against any expansion of established services, it is justified to look at the procedures occasionally and suggest possible modifications which would cost little and at the same time indicate to seamen how they might help themselves by answering the question, "How much weather routing should be undertaken by the ship's master?"

But first, some consideration is necessary on the controversial question of the division of responsibilities in this matter between a ship and a weather or routing service. It is not inappropriate to draw a parallel with a naval or amphibious operation in war.

The captain of a ship is entirely dependent on good communications with his shore base for his advices on enemy intelligence. These so often determine the strategy adopted, but do not relieve the captain of the responsibility for making decisions when the enemy seeks to establish tactical advantage by sudden attack. In such circumstances the man in command on the spot must decide the immediate and necessary action. The entire operation calls for coördinated effort between ships and shore in which the divisions of responsibility are established and understood.

The situation is the same when dealing with adverse weather problems. The man at sea can never be in the position to work out the details of weather development on the hemispheric scale; he must depend upon the national weather services to collect, analyze and present the overall weather picture in the best and simplest possible way. As fas as expense allows, all ships should be equipped with radiofacsimile recorders, and all masters should be trained to use such chart products to their own advantage. This is particularly important for the tactical evasion of rough weather in young storms. However accurate routing services may be, the state-of-the-art of forecasting is such that present day models fail occasionally to cope with rapid development of depressions, particularly those which result from oceanographic features and are dangerous to ships.

The philosophy is being expressed here that the seaman must be able to forecast weather developments in the short term (up to twelve hours ahead) himself. In practice most sailors are excellent single observer forecasters. Conflict may arise here over the weather routing of ships, some zealous companies maintaining that this is best carried out entirely by an operating authority ashore, the master of the ship having no say in the choice of courses. Until such time as weather forecasts are precise for several days ahead, this would be bad procedure. The overall strategical plan for a voyage is indeed best undertaken by the shore-based authority using the well-developed computer services. But the plans must always allow for on-the-spot decisions in the event of weather uncertainty. It follows that mariners need training in meteorological interpretation of synoptic charts, some knowledge of conversion of geostrophic wind speeds to the values at sea surface levels, and an understanding of the creation of dangerous seas and swell in adverse air mass/sea mass circumstances. The overall requirement is for headquarters' staff and the men at sea to appreciate and understand each other's problem and to coordinate efforts in solving them. How much is left to the other depends on the information available to each and the skills of the individuals.

Appendices

APPENDIX A
THE THEORETICAL TREATMENT OF WAVES

A-1 Sinusoidal wave motions. Let us consider the simple case of a stone thrown into a still pool of water. The ripples spread out in concentric circles, and the surface of the water is deformed into wave patterns which approximate to a sine wave shown in Figure A-1.

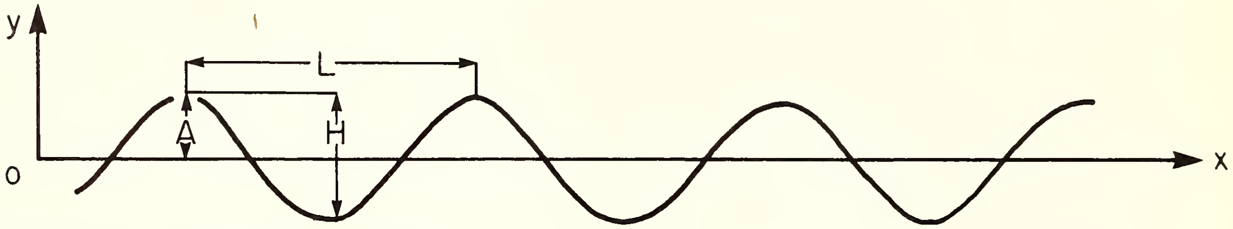

Figure A-1 - A simple sinusoidal wave.

The wave form can be defined as an elementary sinusoidal swell and expressed mathematically by the equation:

$$Y = A \cos 2\pi \left(\frac{x}{L} - \frac{t}{T}\right) \qquad \text{----(A.1)}$$

where x and y are the coordinates with respect to the origin 0,

L = the wave length from crest to crest,
t = time,
T = the period of the wave,
$A = \frac{H}{2}$ where H is the amplitude of the wave or the height from crest to trough.

In reality, the profile of the free surface of waves is only approximately sinusoidal, and the curve is more accurately described as a trochoid (Figure A-2); the slopes up to the crests being slightly steeper than in a sine wave.

The mathematical formulas for trochoids introduce the hyperbolic sines, cosines, and tangents, which involve powers of the exponential quantity, e. The reader is referred to any good textbook on calculus for detail.

Theories of the generation of waves by wind stress are complex, and no mathemetical treatment will be attempted. When the wind is moving faster than the waves, the wave form is as shown in Figure A-3, the slope on the windward side being less steep than on the downwind side. The waves already show some tendency to overturn and break and spray is often torn from the crests.

Much of the theoretical treatment of waves is based on the assumption that a deformed sea surface can be considered as an infinite combination of sinusoidal waves, but for practical forecasting such an assumption can lead to considerable errors in rapidly developing seas due to either wind accelerations or wind flow contrary to currents and tides.

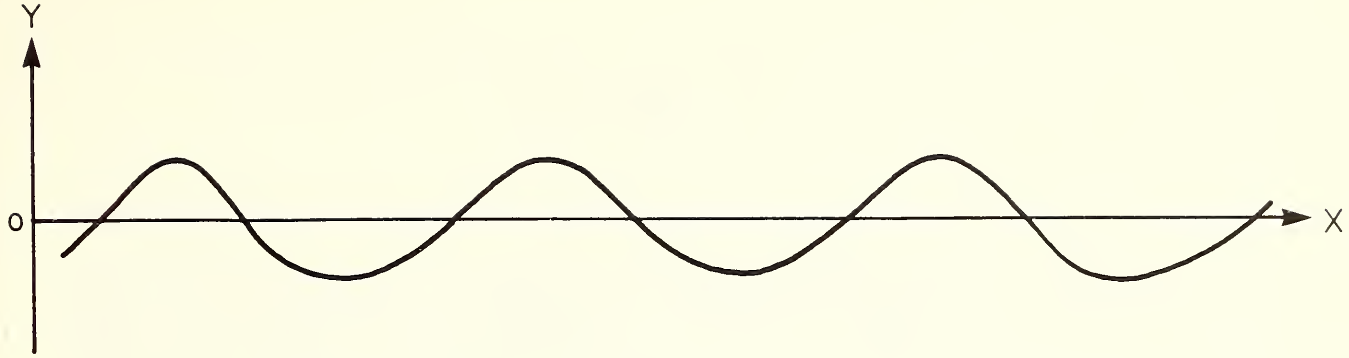

Figure A-2 - Trochoidal motion typical of simple swell progression.

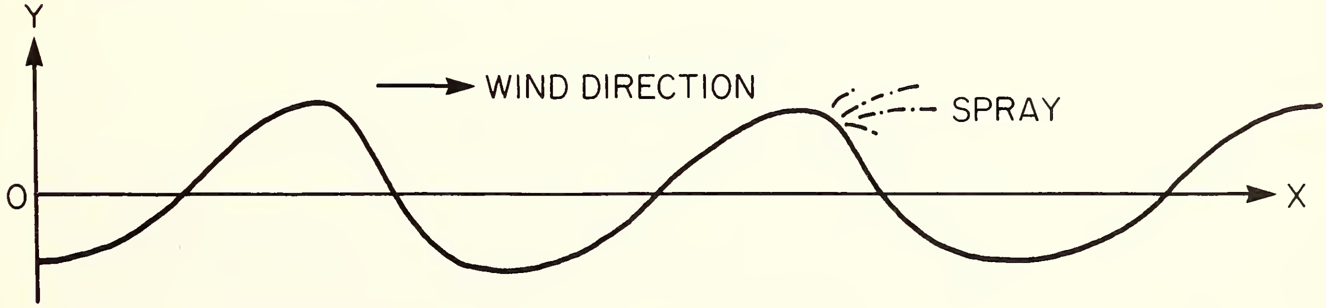

Figure A-3 - Wave motion deformed by a strong wind stress.

A-2 The speed of movement of waves. The speed of progress of a sinusoidal wave is usually denoted:

$$C = \frac{L}{T} \qquad \text{----(A.2)}$$

If, in equation (A.1), we let $k = 2\pi/L$ and $s = 2\pi/T$, the equation can be simplified to the form:

$$y = A \cos (kx - st) \qquad \text{----(A.3)}$$

where k is often defined as the wave number.

It is not the intention to go into mathematical detail in this chapter, and it will be merely stated that for a wave profile it can be proved that the speed of the wave is given by the formula:

$$C^2 = \frac{g}{k} \tanh (kd) \qquad \text{---- (A.4)}$$

where C is the speed of the wave and d is the depth of the water. Substituting for k:

$$C^2 = \frac{gL\tanh(2\pi d/L)}{2\pi}, \qquad \text{----(A.5)}$$

Tanh is a mathematical quantity known as the hyperbolic tangent, approximations for which are given in the next section.

It is immediately seen from this formula that the speed of movement of a wave varies as d/L (*i.e.,* the ratio of the depth of the water to the length of a wave). Depth is of little consequence in "deep" water, but the speed of progress can be reduced considerably in "shallow" water. "Deep" and "shallow" are relative terms since the small capillary waves on the surface of a shallow pond could well behave as deep water waves. Similarly, tsunamis that have wave lengths of tens of thousands of meters behave as shallow water waves when moving over the deepest oceans. An arbitrary distinction is made when the ratio of d/L = ½. (⅓ is really a better figure. See Table A-1). If d/L is greater than ½, the wave is considered to be a *deep water wave.* If d/L is less than ½, the wave is considered to be a *shallow water wave.*

TABLE A-1

VALUES OF $e^{-2\pi d/L}$ and tanh ($2\pi d/L$) CORRESPONDING TO RATIOS OF DEPTH TO WAVE LENGTH BETWEEN 0.05 and 2.0.

d/L	.05	.10	.20	.25	.33	.40	.50	.67	.75	.80	1.00	1.25	1.50	2.00
$\frac{2\pi d}{L}$	.31	.63	1.26	1.57	2.07	2.51	3.14	4.21	4.71	5.03	6.28	7.85	9.42	12.57
$e^{-2\pi d/L}$	.73	.53	.28	.21	.13	.08	.04	.015	.009	.007	.002	.0004	.00008	.000003
tanh ($2\pi d/L$)	.30	.56	.85	.92	.97	.99	Apprx 1	1	1	1	1	1	1	1

A-3 Approximations for movement of waves in deep and shallow water. Let us consider equation (A.5) a little further. Tanh x is an exponential function equal to sinh x/cosh x. If x is a large quantity, sinh x approximates to ½(e^x) and cosh x also approximates to ½(e^x). Thus,

$$\tanh x \cong 1 \qquad \text{----(A.6)}$$

If x is a small quantity, sinh x approximates to x and cosh x approximates to 1. Thus,

$$\tanh x \cong x \qquad \text{----(A.7)}$$

In deep water, d/L is large, and tanh $2\pi d/L$ approaches 1. In shallow water, d/L is small, and tanh $2\pi d/L$ approaches $2\pi d/L$. It follows, then, that in deep water:

$$C^2 \cong gL/2\pi \qquad \text{----(A.8)}$$

In shallow water:

$$C^2 \cong (gL/2\pi) \bullet (2\pi d/L) \cong gd \qquad \text{----(A.9)}$$

Therefore, in deep water the speed of the waves is proportional to the square root of the wave length; in shallow water it is proportional to the square root of the depth.

In dealing with special problems when operating on continental shelves or near sills on the ocean floor relatively close to the coast, it may be necessary to consider a closer distinction between deep and shallow water waves. It will be shown in the next paragraph that the amplitude of the motion of the particles in deep water decreases exponentially with depth. It is therefore advantageous to consider some realistic values of e^{-x} and tanh x where $x = 2\pi d/L$ for various ratios of d/L. These are given in Table A-1 for a range of values from 0.05 to 2.0, which is sufficient to cover most cases that we may wish to consider in practical problems.

For values of d/L greater than .33, tanh $(2\pi d/L)$ is very nearly equal to 1. Also, when d/L is equal to .33, the value of $e^{-(2\pi d/L)}$ is $\frac{1}{8}$.

A-4 Interpretation in practical applications.

In *deep* water the long waves move faster than the shorter ones. Hence, when waves move outwards from a storm area, the waves of long wave length will arrive first at a distant point. This is supported by observation. The first sign of an approaching storm is often a long low swell coming from the direction of a storm. This may be experienced many hours before the arrival of the "seas" associated with the "wind" waves. On many occasions the storm never reaches the area of consideration and the swell alone affects the area.

In *shallow* water the speed of advance depends only on the depth of the water; hence, the waves slow down as the depth of the water decreases. The waves at the rear of the wave train tend to catch up with those ahead resulting in more energy becoming concentrated into a smaller area. Some of the kinetic energy is converted into potential energy with the waves finally becoming top-heavy and breaking.

As waves move from deep into shallow water, a velocity change takes place, and the principle of refraction will apply, as it does when light or sound waves pass through media of different densities. The direction of propagation of the waves must change as the speed of the waves decrease with decreasing depth.

In considering empirical formulae for waves (see Chapter 7), it was seen that the significant height attained by waves is roughly proportional to the wind velocity, although other considerations, such as the stretch of water (the fetch) and the length of time (the duration) of application of the wind to the water surface, are involved. It follows from this that waves of large amplitude and long period are created by very strong winds. The long low swells are therefore caused by storms of considerable intensity, such as hurricanes and typhoons.

From equation (A.2) it is seen that:

$$\frac{1}{T} = \frac{C}{L} = \frac{c}{l}$$

where T = period (a conservative quantity),
C = speed of the wave in deep water,
L = wave length in deep water,
c = speed of the wave in shallow water,
l = wave length in shallow water.

As waves move into shallower water, the speed of advance must decrease with a corresponding decrease in wave length. It should be noted that if the waves move with or against a current or tide, the above relationships break down, since, effectively, the period changes.

Substituting in equation (A.8), we get $C = gT/2\pi$.

Thus, we have for *deep water* waves:

$$C \text{ (in knots)} = 3.03\,T \cong 3T \text{ (in seconds)} \quad \text{----(A.10)}$$
$$C \text{ (in ft/sec)} = 5.12\,T \text{ (in seconds)} \quad \text{----(A.11)}$$
$$L \text{ (in feet)} = 5.12\,T^2 \text{ (in seconds)} \quad \text{----(A.12)}$$

These are approximations which are well worth remembering for practical use. A swell of period ten seconds will advance at a speed of approximately 30 knots, and its wave length will be approximately 512 feet (170 yards) or twelve such wave lengths every nautical mile.

Also, if the length of a ship is about 500 feet, the pitching motion of the ship can become resonant to waves of period ten seconds (approximately).

For *shallow water* waves, $C = \sqrt{gd} = 5.6\sqrt{d}$. Thus, in a water depth of 16 feet, all waves would theoretically be moving at a speed of 22.5 feet per second (or 13.3 knots.).

Ships will tend to roll in sympathy with the waves at much greater periods, but they are designed to counter this. Sympathetic pitching can be much more disconcerting and dangerous, and in extreme circumstances the back of a ship can be broken. These are the ultimate results of the effect known as "slamming," which occurs when the ratio of height to wave length is large. Slamming is most likely to occur when a ship steams too fast into a swell longer than the ship's length and particularly if there is some current running counter to the swell. Both have the effect of reducing wave length and increasing the steepness ratio.

A-5 The movement of the water particles in a wave. If a small object floating on the surface of the water is observed closely when subject to the action of waves, it will be seen that with the passage of a wave crest it tends to move forward a little, but when in the subsequent trough, it moves back. If there is no current there is very little overall progression of the object in the direction of propagation of the waves. Thus, in space, the object is describing a closed curve, and it can be shown that in deep water the closed curve is approximately a circle and in shallow water it is an ellipse. If we consider also particles below the surface, they too must be following closed curves, but not as large as those described by the particles on the surface. The motions are illustrated in Figure A-4. At the bottom, there will be a certain degree of forward and backward motion of the water giving rise to a bottom frictional effect. Waves moving from deep into shallow water are said to begin to feel the bottom as the frictional effect comes into play.

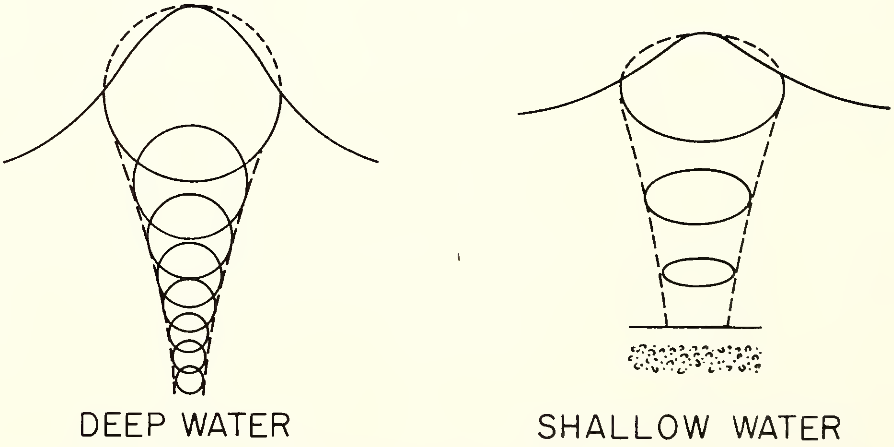

Figure A-4 - Orbital motions in "deep" and "shallow" water.

In deep water the orbits are circles and the components of velocity are:

$$u = A\,s\,e^{-kz}\cos(kx - st) \text{ -horizontally} \quad \text{----(A.13)}$$
$$w = A\,s\,e^{-kz}\sin(kx - st) \text{ -vertically} \quad \text{----(A.14)}$$

where z is the depth below the surface and is positive in the system of coordinates used here. The other symbols have the same meanings as defined above.

Thus, the combined velocity of any particle is Ase^{-kz}, and it follows that the velocity decreases exponentially with depth and is zero at infinite depth.

In *shallow water* the orbits are ellipses and the components of velocity are:

$$u = \frac{As}{kd} \cos (kx - st) \quad \text{-horizontally} \qquad \text{----(A.15)}$$

$$w = \frac{As}{d} (d-z) \sin (kx-st) \quad \text{-vertically} \qquad \text{----(A.16)}$$

When z = d (*i.e.,* at the bottom) the vertical velocity is zero. The horizontal velocity does not involve z and hence, is the same at all levels.

By integrating A.13 and A.14, it is possible to express the displacements of the particles in *deep water.*

$$x = -Ae^{-kz} \sin (kx - st) \qquad \text{----(A.17)}$$
$$z = Ae^{-kz} \cos (kz - st) \qquad \text{----(A.18)}$$

These are circles of radius

$$r = Ae^{-kz} \qquad \text{----(A.19)}$$

The radius of each circle therefore decreases exponentially with depth. A wave of height 30 feet (15 ft. amplitude) and a period of 10 seconds has an approximate wave length of 512 feet. In deep water the particle movement at the surface would be in a circle having a radius of 15 feet as calculated from (A.19) with z = 0. Since d/L = 0.115 is the value at which e exp(-2πd/L) is decreased to 50% of what it is at the surface (Table A-1), we can calculate the depth at which the particle movement is in a circle of radius 7.5 feet This depth is 512 x 0.115 = 57 feet.

In *shallow water* the particles follow ellipses in which the major axis equals 2A cosh k(d-z)/sinh kd and the minor axis equals 2A sinh k(d-z)/sinh kd. These relationships may be simplified as before for shallow water where the depth is less than about one-twentieth of the length of the wave. In such cases,

$$\text{major axis} = 2A/kd = AL/\pi d \qquad \text{----(A.20)}$$
$$\text{minor axis} = 2A(1-z/d) \qquad \text{----(A.21)}$$

Near the bottom the ellipses degenerate into straight lines.

In practice we may frequently need to consider the case of long ocean swells of considerable amplitude moving over continental shelves into shallow water. From a simple consideration of the figures given in Table A-1, it is easy to see that a large wave of amplitude ten meters and wave length of 500 meters at the surface will have an amplitude of 2.8 meters at a depth of 100 meters. This is not inconsiderable.

A-6 The movement of waves in groups (the group velocity). Let us now consider the case in which we have two very similar waves of equal amplitude moving in the same direction, but having slightly different wave length. The periods of the two waves will be approximately equal, but this slight difference will mean that they will become slowly out of phase with one another. At times they will reinforce one another to virtually double the amplitude and later they will almost cancel one another out. In such circumstances an observer sees a train of waves of varying amplitudes, contained within an envelope -itself of sinusoidal form (Figure A-5).

Such a wave sequence has led to the erroneous belief of some mariners that every seventh wave is a large one, although it is observed that large waves on beaches arrive in batches at intervals of several minutes. Surf riders seldom take the first large-looking wave which comes along because experience has taught them that a larger one usually follows soon afterwards.

Let us consider the case mathematically of two such waves of equal amplitude, but of slightly different period and wave length.

$$\begin{aligned} Y_1 &= A\cos(kx - st) \\ \text{and } Y_2 &= A\cos[(k + dk)x - (s + ds)t] \end{aligned}$$

where dk and ds are small increments to k and s.

$$Y_1 + Y_2 = A\cos(kx - st) + A\cos[(k + dk)x - (s + ds)t] = 2A\cos \tfrac{1}{2}[(2k + dk)x - (2s + ds)t]\cos \tfrac{1}{2}[(dk)x - (ds)t] \text{----(A.22)}$$

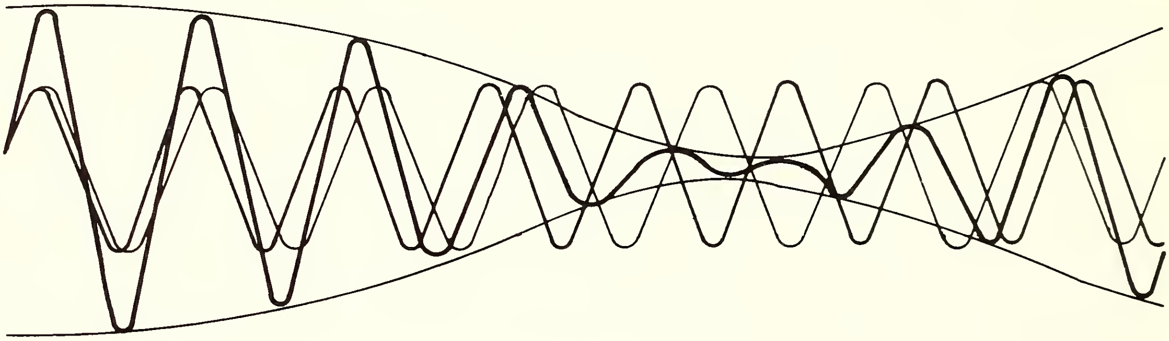

Figure A-5 - Combinations of waves of equal amplitude but slightly different wave lengths.

When dk and ds are small this expression approximates to:

$$Y_1 + Y_2 = 2A\cos(kx - st)\cos \tfrac{1}{2}[(dk)x - (ds)t] \qquad \text{----(A.23)}$$

This equation represents a series of successive waves of amplitude varying between zero and 2A. The term cos $\frac{1}{2}[(dk)x-(ds)t]$ is a modulation factor, and it follows from our consideration of the behavior of the simple wave form that each group of waves will be at a distance apart of $2\pi/dk$ and will follow one another at intervals of time $2\pi/ds$.

Let C_g be the group speed, which is the speed of movement of the group of waves, such as a swell train. Thus,

$$C_g = \frac{ds}{dk} \qquad \text{----(A.24)}$$

But s = kC, where C is the speed of a single wave in the train. Therefore,

$$C_g = \frac{ds}{dk} = \frac{d(Ck)}{dk} = C + \frac{kdC}{dk} \qquad \text{----(A.25)}$$

where $k = 2\pi/L$ and $dk = \frac{-2\pi dL}{L^2}$. Therefore, group speed can be written as

$$C_g = C - L\frac{dC}{dL} \qquad \text{----(A.26)}$$

Using (A.8), we can derive $2C\frac{dC}{dL} = \frac{g}{2\pi}$ for use in the second term of (A.26) from which $L\frac{dC}{dL} = \frac{Lg}{4\pi C}$. This is one-half of $C = \frac{gL}{2\pi C}$. Finally, (A.26) can be expressed as

$$C_g = C - C/2 = C/2 \qquad \text{----(A.27)}$$

Hence, the speed of a group of waves in deep water is one-half of the speed of the individual waves that make up the group. Individual waves in a swell train travel faster than the group speed so that waves are continuously moving ahead of the wave group. These advancing waves die out quickly, and the leading edge of the wave train progresses at speed C/2. It will be shown later that the energy associated with a wave disturbance is propagated at the group speed. Group speed is used to determine the arrival time of waves from a distant storm.

A-7 The drag coefficient. The frictional effect of wind on a water surface creates waves, and the speed with which this is achieved and the amplitude of the waves so generated will depend on the degree of bite that is exercised by the wind on the water in the process. This is expressed in more precise mathematical form as the drag coefficient:

$$C_{10} = \frac{\tau}{\pi U_{10}^2} = \frac{-\overline{u w}}{U_{10}^2} \qquad \text{----(A.28)}$$

where τ is the internal shear stress and a measure of vertical transport of momentum.

It is perhaps obvious from this formula that the drag coefficient will generally be greater in unstable conditions since w is likely to be greater when a cold air mass is tending to sink and undercut the air in contact with a warmer sea surface. The principle can be seen in the case of a cold frontal system, which promotes some vertically downward motion to cause impacting on the water surface.

Measurements made over lakes and on platforms off the coast have shown that the drag coefficient tends to increase with the speed of the wind, and the following empirical formula is quoted from a paper in 1973 by S.D. Smith and E.G. Banke *(Quarterly Journal Royal Meteorological Society,* 429, No. 101):

$$10^3 C_{10} = 0.63 + 0.066\, U_{10} \pm 0.23 \qquad \text{----(A.29)}$$

Some questions arise on the validity of such empirical formulas when wind speeds reach 35 knots and above in which spray amounts increase considerably and increased turbulence is experienced. In forecasting sea and swell generation, wind speeds of less than 20 knots are generally of little consequence. Thus, it becomes important to know how the drag coefficient changes at high wind speeds. It is believed that the formula quoted can be considered valid up to 40 knots at least.

A-8 The energy involved in surface waves. The creation of waves on the surface of the sea indicates a transfer of energy from the atmosphere to the ocean. The longer the wind stress is applied and the greater the area of application, the larger the total amount of energy transferred and the larger the waves become. Ultimately, a "saturation" point is reached. The rate of exchange of energy is then just sufficient to maintain the displacements. When the energy supplied by the wind falls short of this value the waves start to decay.

At any particular instant of time, the sea surface can be considered as represented by the sum of an infinite number of sinusoidal waves of different amplitudes and periods. The total energy encompassed in such a sea state will be the sum of the energy components of the various waves.

The energy involved in a sinusoidal wave can be calculated from the displacement of the water particles from the mean position. It can be shown mathematically that this is directly proportional to the square of the amplitude of the waves. If a unit area of a water wave is considered with the displacements over a complete cycle, it becomes possible to deduce that for one particular wave the average potential energy is

$$E_p = \frac{\rho g A^2}{4} \qquad \text{----(A.30)}$$

Similarly, it can be shown that the average kinetic energy is

$$E_k = \frac{\rho g A^2}{4} \qquad \text{---- (A.31)}$$

And hence, the average total energy is

$$E_p + E_k = \frac{\rho g A^2}{2} = \frac{\rho g H^2}{8} \qquad \text{---- (A.32)}$$

Thus, summating for all the waves:

$$E = \frac{\rho g}{8}(H_1^2 + H_2^2 + \ldots H_n^2) = \frac{\rho g \Sigma H_i^2}{8} \qquad \text{---- (A.33)}$$

It is of note that the energy per unit area contained in a wave is the same as the amount of work required to lift a volume of water of unit surface area through a distance $\frac{H}{8}$.

In Figure A-6, the displacement from the mean position at equal intervals of time are represented by the ordinates a_0, a_1, a_2, a_3, a_4, and so forth.

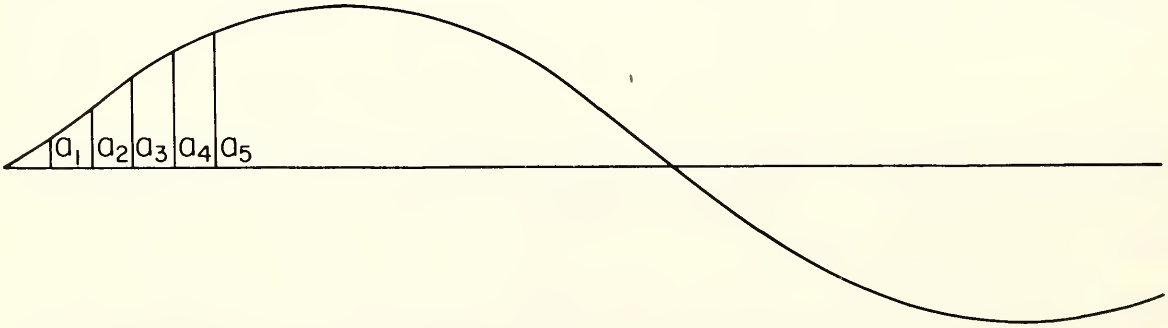

Figure A-6 - Symmetrical wave form.

In the symmetric wave form shown, Σa_i considered over one complete wave form is zero. The variance, σ, can be calculated using

$$\sigma = \sqrt{(a_1^2 + a_2^2 + \ldots a_n^2)/n} \qquad \text{---- (A.34)}$$

It can also be shown that $\sigma^2 = H^2/8$ where H is the amplitude of the wave. Thus,

$$E = \rho g \sigma^2 \qquad \text{---- (A.35)}$$

Therefore, the energy in a wave is directly proportional to the variance of the wave form from the mean level.

APPENDIX B
DEEP OCEAN BUOY SYSTEMS

Since 1971, the U.S. Government, through the National Oceanic and Atmospheric Administration, has deployed moored environmental monitoring buoys in the various oceans off U.S. coasts. Plate 9 shows a typical buoy, which is 12 meters in diameter, about 100 tons in displacement, and with meteorological sensors 10 meters above the waterline. Other buoys are 10 meters in diameter and displace about 60 tons.

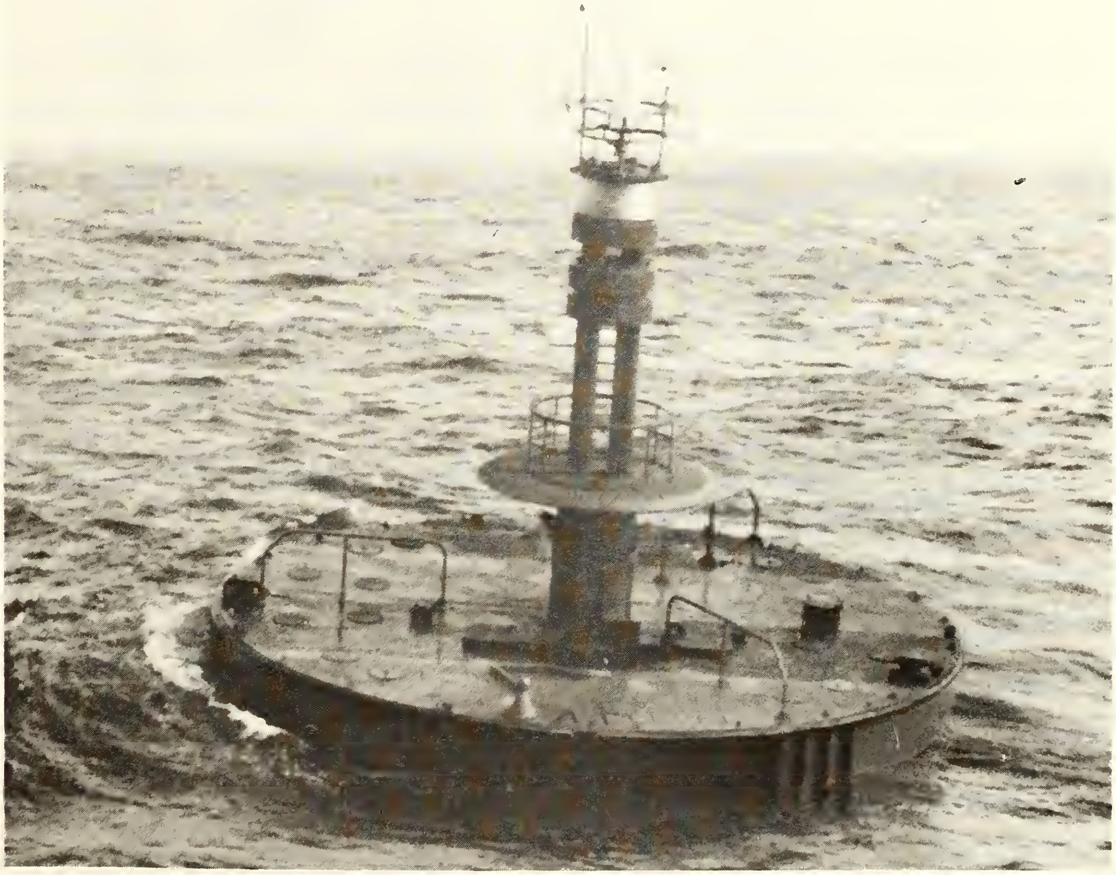

Plate 9 - Environmental buoy. (Photograph courtesy of NOAA Data Buoy Office.)

The number of buoys in operation at any one time varies, but Figure B-1 shows those that were operational around October 1979 along with planned sites for future deployments. All the buoys relay their data through the UHF GOES satellite data relay system, which, in turn, eventually relays it to the National Meteorological Center near Washington, D.C.

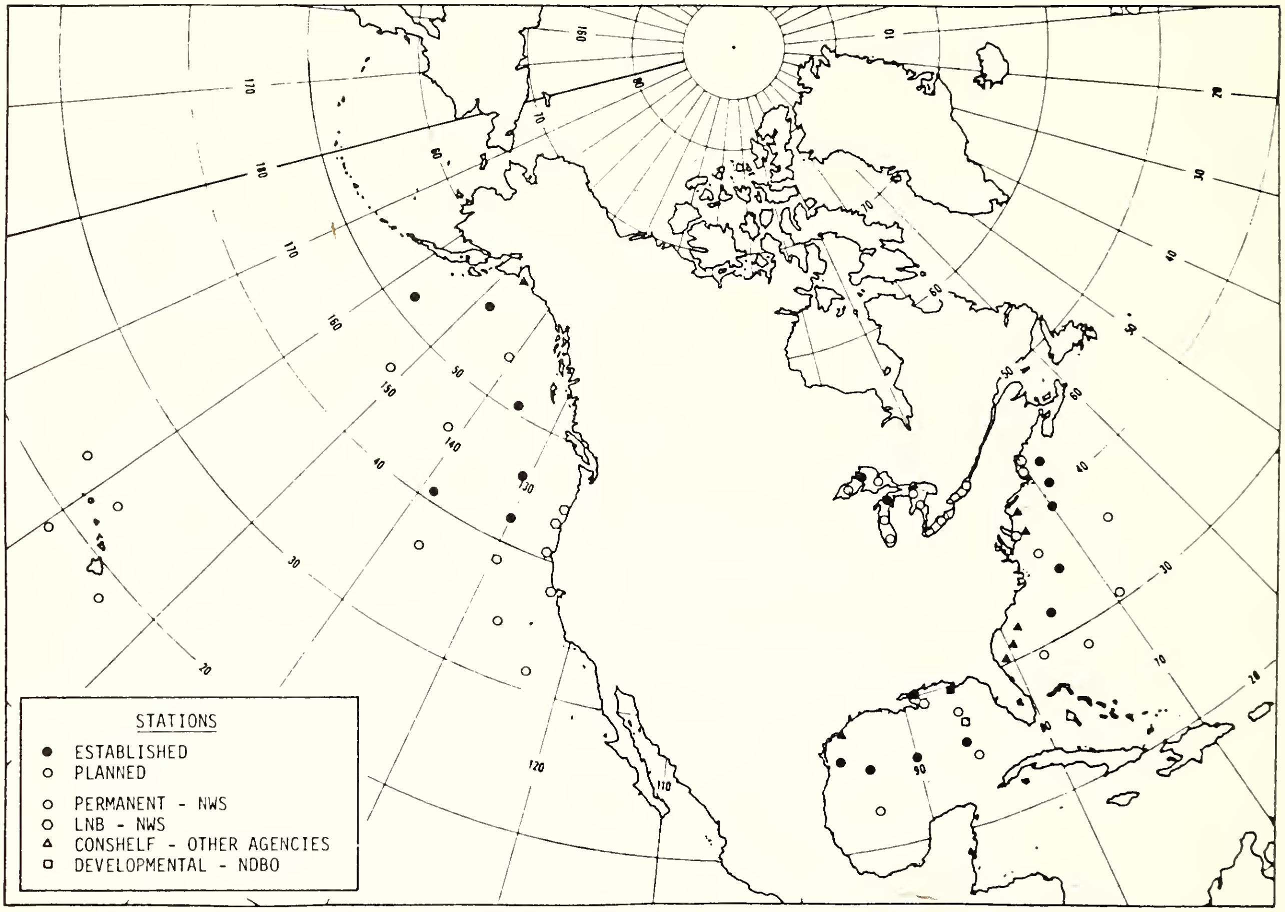

Figure B-1 — Environmental buoy locations for October 1979. Abbreviations used: NWS (National Weather Service); LNB (Large Navigational Buoys); CONSHELF (Continental Shelf); NDBO (NOAA Data Buoy Office). (From *NDBO FY 1980 Technical Requirements.* NOAA Data Buoy Office. October 1979.)

The sensors used aboard the buoys vary somewhat. Table B-1 shows some of the features associated with a typical buoy. As can be seen, wind speed measurements are averaged over a long time period and may often be less than those measured aboard a nearby ship because a human observer does not average dial readings from an anemometer over this long of a period. Also, if seas are rough, the buoy's anemometer may be sheltered from the wind when the buoy is in a deep trough.

TABLE B-1

ENVIRONMENTAL BUOY SENSORS

Parameter[1]	Sensor Type	Reporting Range	Sampling Interval	Averaging Period	Designed Accuracy
Wind speed	Vortex shedder	0 to 80 m/s	1 sec	8.5 min	± 1 m/s
Wind direction	Vane and flux-gate compass	0° to 360°	1 sec	8.5 min	± 10°
Air temperature	Thermistor	-15° to 49°C	8.5 min	8.5 min	± 0.1°C
Barometric pressure	Variable capacitance	900 to 1100 mb	4 sec	8.5 min	± 0.1 mb
Significant wave height[2]	Accelerometer	0 to 281 m	0.67 sec	20 min	± 0.5 m
Wave period [2,3]	Accelerometer	2 to 30 sec	0.67 sec	20 min	± 0.5 sec
Wave spectra	Accelerometer	0.01 to 0.5 Hz (Δf = 0.005Hz)	0.67 sec	20 min	- - -
Surface water temperature	Thermistor	-15° to 49°C	8.5 min	8.5 min	± 0.1°C

[1] Each parameter reported every hour to the National Meteorological Center.

[2] Computed from wave spectra.

[3] Average or spectral peak.

APPENDIX C

TELETYPE SPECTRAL ENERGY DATA FORMATS FROM BUOYS

Since the time that the original manuscript was finished, a new spectral data format came into being and is still being used in the teletype messages of spectral wave data sent to NWS forecast offices and other users. Once the messages are decoded, the information can be used in the manner described earlier in this book.

An actual teletype wave spectral data message is shown below for an environmental buoy in the Gulf of Alaska.

```
WAVE SPECTRAL DATA =

    46001   //560   71490   20001   /2508   31305
    99100   88030   10000   20000   30000   40000   54371   66871   75121   83121
    92721   02411   11781   21481   31451   41281   59860   67760   77740   87580
    96410   06400   15740   24000   33550   43550   52960   62230   71720   81430
    91270   09795   17735   28425   38225
```

The data heading format for the first line of the message is:

NNNNN $//L_aL_aL_a$ $Q_cL_oL_oL_o$ $YYGGi_w$ /ddff $3P_wP_wH_wH_w$

NNNNN — Five digit buoy identification number.

$L_aL_aL_a$ — Latitude of buoy to nearest 0.1 degree.

Q_c — Quadrant of the globe. 1 (N lat. E long.) 3(S lat. E long) 5(S lat. W long.) 7(N lat. W long.)

$L_oL_oL_o$ — Longitude of buoy to nearest 0.1 degree.

YY — Day of month that data were collected by the buoy (01 through 31).

GG — Frame time; the GMT time that the data were collected (00 through 23).

i_w — Units of wind speed. For buoys, $i_w = 1$, meaning that the wind was measured by an anemometer in meters/second.

dd — True direction of wind to nearest 10 degrees.

ff — Wind speed in m/sec.

P_wP_w — Period of significant waves in seconds.

H_wH_w — Wave height in half meters.

Data format for the remaining lines is:

99BBB 88FFF 1VVVE 2VVVE 3VVVE 4VVVE 5VVVE 6VVVE
7VVVE 8VVVE 9VVVE 0VVVE . . . NVVVE

A decimal point is implied at the left of the BBB, FFF, and VVV subfields.

BBB — The frequency increment (in deci-hertz)to be added to the center frequency (FFF-in hertz) to obtain the successive frequencies for the NVVVE groups. For example, 99100 means to add 0.01 Hz to center frequency FFF to obtain the frequency for the 2VVVE group. The 1VVVE group uses the initial frequency contained in the 88FFF group.

FFF — The first center frequency (in hertz) in the spectral density sequence. For example, 88030 means the first spectral group (1VVVE) was measured at a frequency of 0.03 Hz.

N — The leading integer is simply a group indicator for which a frequency has to be calculated using the method above. N goes from 1 through 9 for the first nine groups, then 0 through 9 for groups 10 through 19, and so on.

VVV — The mantissa (only the three most significant digits) of the displacement spectrum at the frequency determined above for that particular NVVVE group. Units are m^2/Hz .

E — The exponent (base 10) used to multiply VVV by in order to determine the proper placement of the decimal. Positive exponents 0 through 4 are simply encoded as 0, 1, 2, 3, and 4. Negative exponents -1, -2, -3, -4, and -5 are encoded as 5, 6, 7, 8, and 9, respectively. Thus, 0 means 1.0; 1 means 10; 2 means 100, and so forth. For negative exponents, 5 means 0.1; 6 means 0.01; 7 means 0.001, and so on. The value obtained indicates which way to move the implied decimal point in front of the VVV group. The following NVVVE groups illustrate this: 11341 has spectral density 1.34; 11345 has spectral density 0.0134; 11340 has spectral density 0.134.

Missing data are indicated by slashes. If the frequency spacing (BBB) changes, a new sequence is established with another set of two sequence indentifier fields (99BBB, 88FFF).

The spectral report above can now be decoded.

46001 — buoy number

//560 — 56.0°N

71490 — Global quadrant 7. 149.0°W

20001 — Day 20 of the month. (In this case it happened to be 20 August 1980.) 0000 GMT. Wind speed measured in m/sec.

/2508 — Wind from 250° true at 8 m/sec (approx. 16 kn).

31305 — Period of significant waves is 13 seconds. Significant wave height is 5 half-meters (approx. 8 ft.).

99100
88030 — Means to add 0.01 to each successive frequency; 0.03 is the first frequency to be used with the first spectral density group, 10000. Table C-1 shows the decoded spectral density values.

TABLE C-1

WAVE SPECTRAL DATA FROM BUOY 46001 FOR 0000 GMT 20 AUGUST 1980

Group Number	f	S(f)
1	.03	0
2	.04	0
3	.05	0
4	.06	0
5	.07	4.37
6	.08	6.87
7	.09	5.12
8	.10	3.12
9	.11	2.72
10	.12	2.41
11	.13	1.78
12	.14	1.48
13	.15	1.45
14	.16	1.28
15	.17	0.986
16	.18	0.776
17	.19	0.774
18	.20	0.758
19	.21	0.641
20	.22	0.640
21	.23	0.574
22	.24	0.400
23	.25	0.355
24	.26	0.355
25	.27	0.296
26	.28	0.223
27	.29	0.172
28	.30	0.143
29	.31	0.127
30	.32	0.0979
31	.33	0.0773
32	.34	0.0842
33	.35	0.0822

APPENDIX D

GLOSSARY

D-1 Beaches. In tidal estuaries and at river mouths, the flow of the currents has considerable bearing on the surf conditions, and these depend on the beach formations that can change rapidly as a result of the movement of solid material, such as sand, shingle, cobbles, and rocks by wave action. The nature of the beach depends on the geological compositon and degree of erosion of the adjacent coastal land. The interpretation of the term "beach" varies with locality and although many beaches are of sand, there are some which are composed almost entirely of pebbles with a wide range in the size and weight of the stones. Harbor bars may be composed of sand with dimensions susceptible to changes in a short space of time or of stones which change postion more slowly or of rocks or coral reefs which are, more or less, permanent features. The term beach is used in a general sense.

D-2 The Coriolis effect. The earth is approximately a sphere making one complete revolution on its axis every day. As a result of this rotation, every particle on the earth, including particles of air in the atmosphere and water in the sea possesses momentum, which is a conservative quantity. It will be greatest on the equator and zero at the poles. When a particle moves relative to the earth, for example, a car moving along a straight highway at 55 mph, it possesses momentum not only from its own power unit but also from the rotation of the earth, and this latter quantity acts to deviate the car from its straight path; to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This is known as the Coriolis effect. Such a tendency to deviate is corrected in the case of a car by the steering actions of the driver.

Thus, in dealing with any dynamical problem of motion over the earth's surface, it is always necessary to take into account the Coriolis effect. By definition, a force accelerates a particle in the direction in which the force is applied. The Coriolis effect behaves like a force in that it causes the moving particle to deviate, but unlike a force it acts at right angles to the path. Hence, it is customary to refer to the Coriolis effect and not the Coriolis force. It has a value $f = 2U\Omega \sin \phi$ where U = velocity of the particle, Ω = angular velocity of the earth, and ϕ = latitude.

Thus, we see that the Coriolis effect depends greatly on the velocity of the particle, but that it is nil at the equator where winds tend to blow directly from high towards low pressure at right angles to the isobars. As the latitude increases, the Coriolis effect increases, and approaching 60°N, the winds approximate more nearly to the direction of the isobars.

D-3 Gyres. When two air masses of different origin and of different density impinge on one another, a wave formation is normally created on the boundary line between them, and this develops with increasing vorticity into a low pressure system. As the warmer of the two air masses is lifted by an undercutting process, the depression occludes.

In like manner, when a warm sea mass such as the Gulf Stream impinges on a cold current such as the Labrador Current flowing down the eastern seaboard of Canada and the United States, wave formations develop on the thermal boundary. An occluding process starts with the warmer less-dense water tending to flow over the colder water. A circulation develops, which is known as a gyre. It is the corresponding phenomenon in the ocean to the low pressure system of the atmosphere and is governed by similar mathematical equations.

The time scales in the two media are very different, however. The lifetime of a depression or low in the atmosphere may only be four or five days whereas a gyre may take several weeks to develop from a tongue formation, and it may persist as an independent circulation within an ocean current for several months. At a certain stage of development, a gyre can no longer be detected from sea surface temperatures, and the phenomenon becomes a subsurface one. Gyres are probably very common features of the ocean circulations, but it is only in recent years that study has been devoted to them. In the neighborhood of the boundary between such cold and warm water currents, the independent circulations that are created lend to considerable variations in current speeds and directions of the main current.

D-4 Isopleths, isobars, isallobars. In forecasting the weather or water movements, meteorologists use synoptic charts on which values of environmental parameters such as pressure, temperature, barometric tendency, and so forth are recorded. As an aid to analysis, lines are drawn on the charts joining places where measured parameters have equal values, and these lines are covered by the general description as isopleths. Thus, it is possible to draw an isopleth over the ocean joining all points where the significant wave height is reported as 20 feet.

In the case of atmospheric pressure, the line is given the specific designation as an isobar.

There is a similar special designation of a line joining points of equal barometric change in a three-hour interval as an isallobar. Isallobars are particularly useful in indicating acceleration of the wind, which has a considerable bearing on sea and swell development.

D-5 Seiches. In an enclosed body of water, such as a lake or a reservoir, standing waves can be created by disturbing the water surface so as to set it oscillating with a resonant period, responsive to the dimensions of the enclosure. Most people are familiar with creating such effects in a bath tub so that water sloshes about. When such resonant effects occur on a large scale in lakes and harbors, the phenomena are know as seiches, and these can be disturbing and dangerous features for ships at anchor or tied up alongside quays or jetties. The irregular formations of the shores surrounding a lake or a harbor do not preclude such resonant motions, and seiches occur in large bays or in harbors which have been built on the shores. The bays can become resonant to certain periods of seas and swell, and the most uncomfortable circumstances are often created by a combination of a long period swell with a short period sea. The resonant waves combine periodically to produce a wave of large amplitude, which will suddenly displace even a large ship ties up alongside so that the mooring lines and wires snap. Certain harbors on exposed coastlines of the major oceans are particularly prone to seiches. The effect can ususally be minimized by building a jetty in a preferred place to reduce the resonance.

D-6 Spring and neap tides. Tides are created by the attraction of the sun and moon on the water surfaces of the earth, the forces of attraction obeying the inverse square law. The moon, although the smaller body, is much closer to the earth; hence, it is the principal tide raising body. At certain times of the month, the moon and the sun will act in conjunction to produce the maximum tide raising forces. This occurs about a day after new or full moon. The range of tides then normally reaches a maximum with tidal currents running strongest. Such tides are known as spring tides. A day or so after the moon is in the first or third quarter, when the tidal forces of the moon and sun are acting at approximately 90° to one another, the tidal ranges are least and the currents are weakest. Such tides are known as neap tides.

However, both the moon and the earth move in elliptical orbits causing the distances from the moon to the earth and from the sun to the earth to vary continuously throughout the year. Thus, some spring tides will be higher than others, and it is possible to speak of a high high tide, a low low tide, a low high tide, or a high low tide.

D-7 Storm tide surges. In any strong wind, the stress on the water surface displaces water downwind and may cause it to pile up in coastal waters, temporarily raising the water level on the exposed shores. The rise in water level may be considerable if the acceleration of the wind is great and there is a gradual slope of the shelf seawards. The motion is a complex one as a result of the Coriolis effect. Time is not available to set up a counter-current at depth to offset the accumulation of water.

Similar effects can also be created by variations in atmospheric pressure. Thus, in any enclosed sea, such as the Mediterranean, a combination of very high pressure over the eastern end with low pressure over the western end will cause the water level to rise above normal near the Strait of Gibraltar and vice versa. Occasionally, the effects can be disastrous when combined with high spring tides; particulary if they are sufficient to rupture coastal sea walls and inundate low lying territory.

The changes exist particularly in semiclosed seas, such as the North Sea, where tidal effects are great; but they can also be considerable in the Adriatic in the Mediterranean where tidal ranges are generally low. A major disaster occurred in the North Sea in October 1952 when a deep depression created a pronounced northerly sea and swell. This occurred simultaneously with a very high spring tide, and the resultant high waters breached the dikes in Holland and also broke down coastal barriers on the east coast of England. Hundreds of square miles of low-lying land were flooded; there was considerable loss of life. Similarly, storm surges in the Adriatic seriously imperil the survival of Venice. The city was built on islands and wooden piles only a few feet above sea level, and once or twice a year the city is flooded by a storm tide surge enhanced by a seiche effect in the Adriatic Sea. The situation has assumed such critical proportions that the city's survival beyond the end of the century is in some doubt.

Some countries have storm tide surge warning services to give as much notice as possible of such occurrences.

D-8 Tsunamis. Tsunamis are giant waves caused by volcanic eruptions under the sea or by subsurface landslides at geological faults. They are more commonly known as tidal waves, although they are not related to the tides in any way. Tsunamis are waves of long period (15 to 20 minutes in some cases) which race across the oceans at high speeds that may exceed 400 knots. On the high seas they present little danger to shipping and they may not even be noticed. However, it is a different matter in coastal waters where they have been the cause of major disasters with heavy losses of life. The effect experienced is one of a sudden rising of the water level by several feet causing shoreside buildings just above the high water level to be inundated and often destroyed. There is usually a train of high waves caused by the disturbance. The first wave is not necessarily the most destructive. After the first flooding, the sea retreats, leaving the sea shore exposed for some distance from the coast. But the waves in a wave train which follow several minutes later are often devastating. An international warning system of tsunamis is now well established, and, generally, exposed coastal harbors can be given a few hours notice of the likelihood of the event. In general, ships should seek to be at sea in deep water well away from the coast for several hours after the issuance of a warning.

The explosion in 1883 of the volcano Krakatoa in the Sunda Strait to the east of Java is remembered as the cause of one of the world's major disasters in the last century. Many thousands were drowned in the neighboring islands, and the wave effects were recorded at tide gauges in every ocean of the world.

D-9 Upwelling. Upwelling is caused by a wind stress on coastal waters, which acts so as to displace the surface water seawards. To compensate for this displacement of surface water away from the coast, a corresponding inflow occurs along the sea bottom towards the shore with water rising to the surface along the coastal strip. This vertical circulation is more easily generated in the summer months when solar heating causes stratification in the surface layers above the seasonal thermocline so that slipping occurs between the layers. If the circulation is strong enough, the water along the coastal strip is slowly replaced by water from some depth, which will usually be several degrees colder than the surface water and frequently of different composition, being richer in nutrients than the original surface water. This may be attractive to certain classes of fish; any information on upwelling is of great interest to fishermen.

Upwelling is a particular feature of the western coastlines of the continents of Europe, Africa, and North and South America in summer. The sub-tropical high pressure systems often extend northward to cover coastal areas, and the north to northeast winds (south to southeast in the Southern Hemisphere) are sufficiently persistent and strong enough to create the offshore flow of water. The Coriolis effect, once a current has been generated, acts in such a way as to augment the flow of the surface water seawards and aids the upwelling process.

Selected Bibliography

(A) General Texts (non-mathematical)

Bascom, Willard. *Waves and Beaches.* Garden City, New York: Anchor Books, 1980.

Crawford, William P. *Mariners Weather.* New York: W.W. Norton Co., Inc., 1978

Draper, Laurence. "Freak Ocean Waves." *Oceanus,* 10, No. 4 (1964), 13-15.

____________ . "Severe Wave Conditions at Sea." *Journal of the Institute of Navigation,* 24, No. 3 (1971).

Forsdyke, A.G. *Weather and Weather Forecasting.* New York: Grossett and Dunlap, 1970.

Kotsch, William J. *Weather for the Mariner.* Annapolis: U.S. Naval Institute Press, 1977.

Lehr, Paul E., R.W. Burnett, and Herbert S. Zim. *Weather.* New York: Simon and Schuster, 1957.

Lumb, F.E. "A Simple Method of Estimating Wave Height and Direction Over the North Atlantic." *The Marine Observer,* 33, No. 199 (1963), 23-29.

McCollan, Jim. *The Yachtsman's Weather Manual.* New York: Dodd, Mead, and Co., 1973.

Pike, Dag. *Power Boats in Rough Seas.* Camden, Maine: International Marine Publishing Co., 1974.

Robb, Frank. *Handling Boats in Heavy Weather.* New York: Quadrangle/The New York Times Book Co., 1965.

Townsend, Sallie and Virginia Erics. *Boating Weather.* New York: David McKay Co., Inc., 1978.

Vaughn, Cornish. *Ocean Waves and Kindred Geophysical Phenomena.* Cambridge, England: Cambridge University Press, 1934.

Watts, Alan. *Instant Weather Forecasting.* New York: Dodd, Mead, and Co., 1968.

Whelpley, Donald A. *Weather, Water, and Boating*, Cambridge, Maryland: Cornell Maritime Press, Inc., 1961.

(B) More Advanced Texts

Burdwell, Gerald B. and Gordon C. Shields, *Western Region Sea State and Surf Forecaster's Manual.* NOAA Technical Memorandum WBTM WR 51. Salt Lake City: NWS Western Region Headquarters, 1970.

Darbyshire, J. "An Investigation Into the Generation of Waves When the Fetch of the Wind is Less Than 100 Miles." *Quarterly Journal of the Royal Meteorological Society,* 82, No. 354 (1956), 461-468.

Enfield, David B. "Prediction of Hazardous Columbia River Bar Conditions." Thesis. Oregon State University, 1973.

Fett, Robert W., et al. *Navy Tactical Applications Guide: Environmental Phenomena and Effects.* Vol. 2. U.S. Naval Doc. NAVENVPREDRSCHFAC Technical Report 77-04. Monterey, California: Naval Environmental Prediction Research Facility, 1979.

Gelci, R., H. Cazale, and J. Vassal. "The Spectroangular Method of Forecasting Ocean Waves." Ministere des Travaux Publics et des Transports, Meteorologie Nationale (Paris). Trans: Fleet Numerical Weather Facility, Postgraduate School, Monterey, 1958.

Gelci, R., P. Chavy, and E. Devillaz. "Numerical Treatment of the State of the Sea." *Cashiers Oceanographiques,* 15, No. 3 (1963), 153-160. Trans. Fleet Numerical Weather Facility, Postgraduate School, Monterey.

Handbook on Wave Analysis and Forecasting. W.M.O. Document 446. Geneva: World Meteorological Organization, 1976.

Jannuzzi, John A. *Spectral Techniques in Ocean Wave Forecasting.* NOAA Technical Memorandum NWS WR-133. Salt Lake City: National Weather Service, Western Region, 1978.

Kinsman, Blair. *Wind Waves-Their Generation and Propagation on the Ocean Surface.* Englewood Cliffs, New Jersey: Prentice Hall, Inc., 1965.

McLellan, Hugh J. *Elements of Physical Oceanography.* Edinburgh, England: Pergamon Press, Ltd., 1965.

"Meteorological Services of Marine and Coastal Activities." *Proceedings of the Regional Training Seminar, 1-12 April 1974, Rome, Italy.* Geneva: World Meteorological Organization, 1974.

Neumann, Gerhard and Willard J. Pierson, Jr. *Principles of Physical Oceanography.* Englewood Cliffs, New Jersey: Prentice Hall, Inc., 1966.

Pierson, Willard J., Jr., Gerhard Neumann, and Richard W. James. *Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics.* H.O. Pub. No. 603. Washington, D.C.: U.S. Naval Oceanographic Office, 1971.

Roll, Hans U. *Physics of the Marine Atmosphere.* New York: Academic Press, 1965.

Schumann, E.H. "High Waves in the Agulhas Current." *South African Shipping News and Fishing Industry Review,* March 1975.

Shore Protection Manual-Vol. 1. U.S. Army Coastal Engineering Research Center. Washington, D.C.: U.S. Government Printing Office, 1973.

Smith, S.D. and E.G. Banke. "Variation of the Sea Surface Drag Coefficient with Wind Speed." *Quarterly Journal of the Royal Meteorological Society,* 101, No. 429 (1975), 665-673.

Williams, Jerome. *Oceanography.* Boston: Little, Brown, and Co., 1962.

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