Climate and Fisheries

Proceedings
from a Workshop
held March 29–31, 1978

Center for Ocean
Management Studies

Climate and Fisheries

Proceedings from a workshop on the influence of environmental factors on fisheries production

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COMS

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Preface

The passage of the Fishery Conservation and Management Act of 1976 has emphasized the need for greater understanding of the factors that determine the variability in fish production and distribution. Although much of this variability is related to changing environmental conditions, all who have examined this matter are aware that these relationships may be extraordinarily complex.

The past few years have witnessed some progress in the understanding of coastal and continental shelf ecology and in the understanding of the physical processes that occur in these areas. However, with a few notable exceptions, the community of coastal ecologists and fishery biologists have had little direct interaction with the physical oceanographers and meteorologists who are concerned with the physical processes of these regions.

For these reasons, and because of the recent interest in the role of climate on all food production, including fisheries, the time seemed propitious to call together a representative group of experts in these different areas to exchange views and ideas on the general subject. Support for this two-and-a-half-day workshop came from the Environmental Data Service of NOAA. The workshop was sponsored by the University of Rhode Island's Center for Ocean Management Studies (COMS) and was held March 29 to 31 at URI's Alton Jones Conference Center. A list of the attendees and of the steering committee who ran the workshop is appended at the end of these proceedings.

The goals of the workshop were modest. At the minimum we hoped for a useful exchange of views about the environmental factors that influence fish production. At a second level we hoped to produce a document that would provide the interested scientist with sufficient information so that he or she could quickly find the way to relevant literature. Finally, we hoped it might be possible to reach a consensus on where we are, what our prospects are for the future, and what we might do to improve those prospects.

The reader must take on faith that we did indeed have a useful exchange of views and that we learned from each other. Our second goal was achieved by the production of a series of review papers which comprises the major portion of this volume. In a few cases it was necessary to limit the review to the waters off the northeastern United States. The review papers (drafts of which were available at the conference) have been supplemented by a number of case studies which were discussed at the workshop.

On the afternoon of the second day the group broke into four panels to discuss a series of questions which had been raised during the workshop. The views of these panels, or working groups, were discussed in plenary sessions the third day, and their reports are included in a separate section. The summary that follows represents the chairmen and rapporteurs' attempts to amalgamate the views of the working groups, a first draft of which was circulated to all attendees after the conference and revised accordingly.

John Knauss
Workshop Chairman

Summary

The workshop was cautiously optimistic about making appreciable progress in the next few years in understanding the relationship between fish production and environmental variations. It was generally believed that there were at least a half-dozen commercial species on each coast on which it might be feasible to build climate/fisheries models. It will not be easy; therefore, we should begin with those species for which we have the best catch and production statistics, environmental information, and life history studies.

Evidence to date suggests that environmental factors have the greatest impact during larval stages; thus, understanding the factors which control larval survival is critical for any successful climate/fisheries model. At the risk of oversimplification, the factors can be split into two broad categories:

(1) those species which require favorable circulation patterns for survival. For example, it has been shown that menhaden are spawned offshore but the larvae must drift onshore to find sufficient food.

(2) those species which benefit from synchronous timing of their reproductive cycle with the productive cycles of species with which they interact (prey, predators, competitors). For example, it appears that the Pacific anchovy larvae off California thrive on certain species of dinoflagellates. To the extent that the anchovy spawning matches the timing of the dinoflagellate blooms, good year-class recruitment can be expected. A mismatch in these cycles suggests a poor year class.

Each category probably plays a role in the successful recruitment of any given species, but there was general consensus that it will be easier to develop predictive climate/fisheries models for those species which need favorable circulation patterns to control larval survival than for the species whose survival is geared to a match/mismatch of either food or predators. However, in either case it should be possible to develop observational programs to verify proposed relationships. It was further noted that "empirical models" require less fundamental understanding of these interactions than do "process models," but the former require a more substantial data base, usually in the form of longer time series.

A number of participants stressed the point that in all probability the essential environmental/fisheries relationships are highly nonlinear and we should be prepared to think in terms other than linear correlation relationships or interactions. As an example, there was the suggestion that it would be useful to determine the critical conditions which lead to catastrophic mortality, such as unusually high or low seasonal temperatures, extraordinary freshwater outflows, low dissolved oxygen concentrations, or unusual density stratification.

Knowing that a catastrophic event is pending could change management strategies. For example, if one recognized a high probability for a major anoxic event such as occurred off New Jersey in the summer of 1976, one might be tempted to encourage a heavier harvest of the surf clam in the spring, since the clams would die in late summer anyway.

The desirability for fishery scientists and marine biologists to play a more active role in the United States Climate Program was stressed not only because it is believed that this program can contribute to fisheries but because biological indicators may be sensitive measures to climatic change — for example, the population explosion of the green crab population in New England waters during the warming trend of the 30s and 40s.

There was a general consensus that much more could and should be done to increase communication between fishery and marine biologists, physical oceanographers and meteorologists, although there was not always agreement on the ways to achieve this. The communication problem is particularly acute on the East Coast, and there was general consensus that the East and Gulf Coasts needed a regular meeting, perhaps modeled after EPOC (Eastern Pacific Oceanographic Conference), which has been held regularly on the West Coast for more than 20 years. Strong but not universal sentiment was also expressed for putting together small interdisciplinary task teams which could work on specific problems. No one suggested that these task teams should be based at a single location. Although the physics and biology may be common, each climate/fisheries model is regionally specific and can probably best be attacked on a regional basis.

In much of the discussion at the conference, the attendees were concerned about what could be done to advance our understanding of the role of environmental variations in specific fisheries (for example, determining the role of warm core eddies and Gulf Stream meanders in the survival of the planktonic larvae of haddock on Georges Bank), and these discussions cannot be easily summarized. However, there were a number of common threads:

(1) the need for better (longer) time-series data, and the need for more systematic monitoring data, is clear, as is the opportunity to acquire at least some of these data through ships and aircraft of opportunity, and satellites such as SEASAT. However, the costs of such efforts are not trivial, and there was a general reluctance to suggest specific programs in the absence of a testable hypothesis.

(2) There is a need for better documentation of historic trends, such as the shifts in population with time, which is presumably related at least in part to climatic variation, and the effects of catastrophic events on local fisheries, such as Hurricane Agnes on the Chesapeake Bay fishery.

(3) If we are to understand the environmental factors affecting fish production, we must have an accurate understanding of the life cycles of the fish involved. For many commercial species our knowledge is limited (particularly in the early life stages), and even for those species best studied further study would in all probability bring forth new and important information.

(4) We are probably at the stage in certain climate/fisheries models (such as East Coast menhaden) where we can begin critical model testing. However, it must be recognized that it might take a number of years to verify such models, and yet it would be a mistake to sit on one's hands for ten years while a single model was being tested.

Finally, there was general agreement that the development and implementation of rational management practices as required under the Fishery Conservation and Management Act is both a great responsibility and a challenge to our ability to apply our knowledge of the oceans to the development of management plans. Those that are in effect today are the product of many years of research. Improvement in these plans can come only through a balanced program of short- and long-term and basic and applied research.

Working Papers

Physical Processes, and Their Scales, of Possible Significance to Fisheries, Especially off the Northeastern United States

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Introduction to the Climate and Fisheries Problem

The oceanic circulation is largely driven by the sun, with the atmosphere serving as a working fluid. A portion of the solar driving of the ocean is provided directly by thermal radiation but much of the driving is more indirect, involving the intervening atmospheric processes which generate the atmospheric circulation. For example, the distribution of the air-sea transfers of momentum, heat, and moisture is largely governed by the atmospheric circulation produced by solar heating of the atmosphere. Thus, the air-sea transfers, which drive the ocean, have spatial and temporal patterns that are controlled by the structure and variability of atmospheric circulation systems. More fundamentally, the air-sea transfers are influenced by variations of the solar driving which can be recognized in diurnal, seasonal, and latitudinal variations in oceanic properties. Variations in solar heating associated with long period orbital parameters of the earth-sun system can be expected to give rise to fluctuations in the oceanic circulation on climatic time scales.

As we understand the concerns of contemporary fisheries management, the problem of climate is that of interannual variability in the production and distribution of fisheries stocks over a time domain of a decade or so. A portion of that variability is due to fishing activity. Other portions are presumably due to natural variability in the oceanic circulation system, which affects the supply of food and the dispersal of larvae, and to physical transports of deleterious, anthropogenic, biogeochemical anomalies which have unsteady sources or to which the ocean has not yet equilibrated (see Nakao, 1977, and Tont, 1976). Of course, some attribute variability in fisheries stocks to purely random biological and physical events. That is a pessimistic view and can be a crutch for a lack of understanding. The only hope for a predictive knowledge useful for fisheries management rests with causality, a prospect which is amenable to hypothesis formulation and testing. Even if deterministic relations are difficult to establish, intervariable relationships may be established in the conceptual framework of statistical aggregates. For our purposes, the concern is with physical transport processes and their variations, especially interannual variations in the seasonal circulation and exchange processes. Here we do not mean only year-to-year variability in the amplitude, phase, and shape of a seasonal cycle; we also include the occurrence of relatively rare or extreme events or episodes, and the interannual variability in synoptic scale variability. The approach must be to examine (1) what we know about circulation and exchange processes and their interannual variability, (2) the causes of this variability and to what extent those causes can be modeled, and (3) the consequences to fisheries of this variability. Once all the linkage in the chain of natural events is identified, then it is a question of determining how efficient the chain is, or how high the signal-to-noise ratio may be, and whether information about the chain of events can be used to advantage for fisheries management purposes.

One reason to be sanguine about future understanding of the climate as defined above is that studies of interannual variability are only in their infancy and are already providing new insights. For

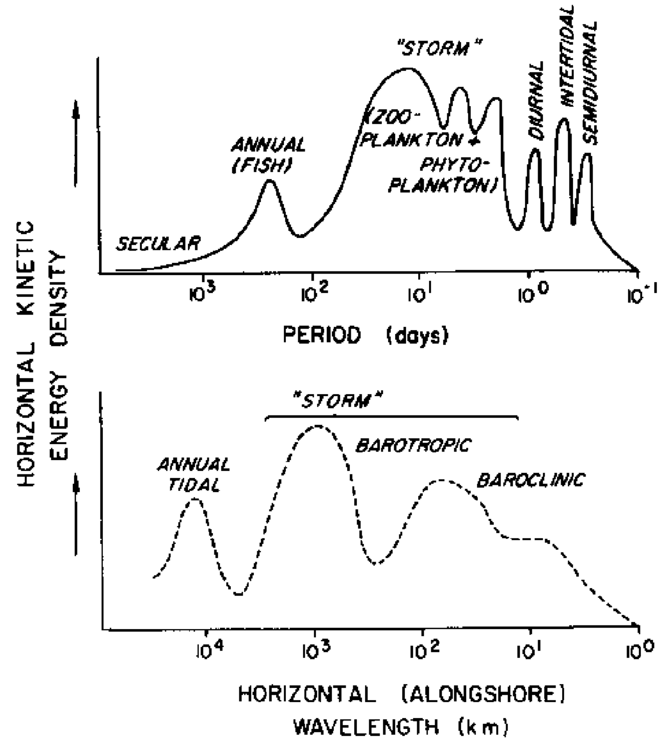

Figure 1. The frequency (upper panel) and horizontal (alongshore) wave number (lower panel) spectra of horizontal kinetic energy. (Note: Solid curve is fairly well established; dashed curve is quite uncertain.)

example, there are global scale patterns in the atmosphere and ocean with a quasi-biennial periodicity which now begin to relate phenomena from polar to tropical latitudes. A case in point is the anomalous winter of 1976 over North America and the el Niño of 1976 off South America. An example of a recent report on planetary scale forcing is to be found in McGuirk (1978).

The objective of this paper is to convey, even if only in cursory terms, our present understanding of ocean circulation phenomena, with special emphasis on fisheries-related phenomena and the extended jurisdiction zone off the northeast United States. This paper cannot attempt to be complete, but it aspires to assist the interested reader in locating some of the contemporary literature, and in guiding the reader with some of the physical concepts which may be particularly pertinent. No small part of the problem is due to the fact that several "literatures" need to be consulted; that is, those of several disciplines and those found in professional journals and in governmental reports. In the latter category, reports on the present subject coordinated by Gehringer and Austin (1976) and Goulet and Hayes (1977) are noteworthy.

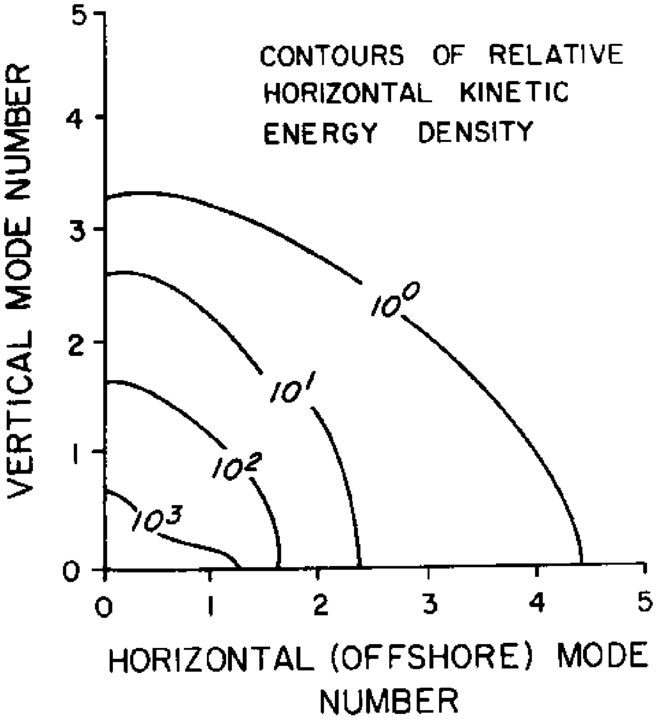

Figure 2. The distribution of horizontal kinetic energy over vertical and horizontal (offshore) modes.

Scales and Relationships

Circulation has a frequency-wave number spectrum whose structure is known in some broad outline form. Figures 1 and 2 schematize the distribution on continental shelves of horizontal kinetic energy (proportional to the horizontal velocity squared) over Fourier coordinates of frequency and horizontal (alongshore) wave number, and of horizontal (offshore) and vertical mode numbers, respectively. (The mode numbers correspond basically to the number of zero-crossings in the horizontal velocity along a particular coordinate; thus, they are a measure of the amount of spatial structure in that coordinate.) The frequency and alongshore wave number spectra tend to show a "lumpy" distribution, with spectral gaps in between. Also suggested is that the energetic "storm-time scales" are well matched to the phytoplankton and zooplankton growth rates, whereas the seasonal or annual time scale is matched to the growth rates of fish. The energy distribution over horizontal (offshore) and vertical mode numbers indicates that most of the energy is found in modes of motion with relatively simple vertical or cross-shelf dependence, perhaps one or two current reversals with depth and with distance offshore. We know the frequency and vertical mode spectra fairly well, but our knowledge of the offshore horizontal mode and alongshore horizontal wave number spectra is weak. Ultimately, we need to know the joint distribution of horizontal kinetic energy and other quantities over the four Fourier coordinates. Much of the physics may be delineated in this Fourier space, including the interactions of processes of different scales. Different parts of the space are governed by different dynamics. There is a possibility that not all physical scales are of importance (or at least of equal importance) to biological processes. Here it is assumed that steady and transient circulation phenomena are of prime importance to fisheries, as opposed to, say, small-scale turbulence. Since the energy is not distributed uniformly in Fourier space, and spectral gaps separate relatively energetic bands, various processes can be isolated in models and experiments to some extent, which is a great advantage.

The parts of the spectrum we are primarily concerned with are influenced by:

(1) the Earth's rotation, as represented by the vertical component of the Coriolis parameter, $f = 2\omega_e \sin(\theta) \sim 10^{-4}\text{sec}^{-1}$ at mid-latitudes, where ω_e is the Earth's angular rotation rate and θ is the latitude and its latitudinal variation, $\beta = \frac{1}{R_e}\frac{df}{d\theta} = \frac{2\omega_e}{R_e}\cos(\theta) \sim 2 \times 10^{-13}\text{cm}^{-1}\text{sec}^{-1}$, where R_e is the Earth's radius;

(2) the ocean's density stratification and depth, as represented by the external (shallow water) gravity wave phase speed, $c_o = \sqrt{gD}$, g the acceleration of gravity and D the water depth and the internal gravity wave phase speed $c_1 = \overline{N}D$, where $\overline{N}$ is the depth-averaged static stability, $N = \sqrt{\frac{-g}{\rho}\frac{\partial\rho}{\partial 2}}$, and ρ is the mass density;

(3) variable topography as represented by bottom slope $\alpha = |\nabla_H D|$ and shelf width, L_s.

The effects of rotation, stratification, and depth are combined to form two length scales: $L_o = \frac{C_o}{f}$, the external radius of deformation, and $L_I = \frac{C_I}{f}$, the internal radius of deformation. If $L_s \sim 200$ km, $L_o \sim 2{,}000$ km, and $L_1 \sim 20$ km on the shelf ($L_1 \sim 50$ km in the open ocean), then, because $L_1 \ll L_s$, baroclinic (internal) motions can be tightly trapped on shelves, while, because $L_o \gg L_s$, barotropic motions will not be trapped unless modified by variable depth. Coastal upwelling zones, geostrophic jets, oceanic fronts, and mid-ocean eddies have a width of the order of L_1. Tsunamis propagate with a speed C_o, and mid-ocean baroclinic eddies with a speed $C_R \sim \beta L^2$, ~ 5 cm/sec. In this fashion, a set of length and time scales are developed to determine model or observational grid size, and to measure the size, in nondimensional terms, of circulation phenomena. For example, if a storm advances with a speed C, then: (1) if $C > C_o$, the oceanic response is mainly in the form of external gravity waves, (2) if $C_1 < C < C_o$, the response is mainly in the form of internal gravity waves, and (3) if $C < C_1$, the response will be mainly upwelling. The concepts outlined above, and more complete versions, have been developed in recent years and are largely traceable to Charney (1955).

The surface Ekman transport, $\vec{M}_e$, is the depth-integrated mass transport produced by the action of a wind stress on the sea surface, where

$$\vec{M}_e = (M_{ex}, M_{ey}),$$

$$M_{ex} = \frac{\tau_{wy}}{f},$$

$$M_{ey} = \frac{-\tau_{wx}}{f}, \text{ and}$$

$$\vec{\tau}_w = (\tau_{wx}, \tau_{wy})$$

is the surface wind stress. $\vec{M}_e$ is orthogonal to $\vec{\tau}_w$, to the right in the Northern Hemisphere. Typically, $\vec{\tau}_w$ must be evaluated from a bulk aerodynamic parameterization; for example, the quadratic stress law

$$\vec{\tau}_w = \rho_a C_D |\vec{V}_{10}| \vec{V}_{10}$$

is often used, where ρ_a is the mass density of air, C_D is the drag coefficient, and $\vec{V}_{10}$ is the wind velocity at 10 m height above the sea surface. Frequently used values for ρ_a and C_D are 1×10^{-3} gm/cm^3 and 2×10^{-3}, respectively. Hence, for a 20-knot (10 m/s) wind, $|\vec{\tau}_w| \simeq 2$ dynes/cm^2. There is a substantial (factor of 2) uncertainty in C_D (which may be a function of $\vec{V}_{10}$, etc.) and an uncertainty as to how to measure $\vec{V}_{10}$ well at sea. Also, $\vec{\tau}_w$ has a spectrum which must be considered in observation and application. The ocean circulation is largely wind-driven, and it is advisable to be reminded anew of fundamental uncertainties in the basic variable, $\vec{\tau}_w$. At mid-latitudes, where $f \simeq 10^{-4}$ sec^{-1}, our 10 m/s wind produces an Ekman mass transport of 2×10^4 gm cm^{-1} sec^{-1} or a volume transport of 2×10^4 cm^2/sec per unit cross section, 90° to the right of the wind direction. Distributed over a 10 m thick layer, this is equivalent to a 20 cm/sec flow. (In addition to an estimate of the flow in the surface mixed layer, it is often useful to have an estimate of the water velocity at the sea surface per se. A fairly reliable estimate can be obtained as 3 percent of $\vec{v}_{10}$. In our example, that equals 30 cm/sec in the same direction as the wind.)

The offshore Ekman transport, or coastal Ekman divergence, produces coastal upwelling. As Yoshida (1955) noted, since coastal upwelling occurs within L_1 of the coast (oriented along y), then the vertical (upwelling) velocity must be

$$W_e = \frac{-M_{ex}}{\rho_o L_I} = \frac{-\tau_{wy}}{\rho_o L_I f} \simeq 10^{-2} \text{ cm/s.}$$

If the pycnocline is initially at a depth H, then it will surface at roughly

$$t_s = \frac{H}{W_e} = \frac{\rho_o H C_I}{\tau_{wy}} .$$

For our example above and H = 30 m, $t_s = 3 \times 10^5$ sec or three days for a typical upwelling spin-up time.

Open ocean upwelling is induced by the divergence of Ekman transport produced by a wind-stress curl; in other words, the vertical velocity, w_e, at the base of the Ekman layer is

$$W_e = \frac{I}{\rho_o} \nabla_H \cdot \vec{M}_e = (\nabla \times \frac{\vec{\tau}_w}{\rho_o f})_V$$

and it is called Ekman suction (pumping), upwards (downwards). To the extent that open ocean upwelling is important to fisheries, this relationship for Ekman suction sets some priority for resolving the spatial structure of the surface wind field on the scale L_1. This may be accomplished, in part, with hourly sampling and space-time conversion.* The Ekman transport and suction relationships are valid for fluctuation time scales, T, which are much greater than f^{-1}. The winds do vary more rapidly and the above relationships can be generalized to include time derivatives. With winds which vary in speed or direction on a time scale of order f^{-1}, additional phenomena are generated, such as near-inertial motions and wind-stirring (deepening) and cooling of the upper layer by turbulent entrainment.

The geostrophic mass transport, $\vec{M}_g$, is the major circulation component, where

$$\vec{M}_g = (M_{gx}, M_{gy})$$

$$M_{gx} = \int_z^{\zeta} \rho_o U_g \, dz, \; M_{gy} = \int_z^{\zeta} \rho_o V_g \, dz$$

$$U_g = \frac{-g}{\rho_o f} \partial_y (\zeta + \phi), \; V_g = \frac{g}{\rho_o f} \partial_x (\zeta + \phi)$$

$$\phi = \int_z^{\zeta} \rho \, dz$$

ζ is the sea surface height and contributes to the barotropic pressure gradient, while ϕ is the analogous contribution of the density field to the baroclinic pressure gradient at depth z. To evaluate this flow component, the density field and sea surface height or some equivalent (surface velocity, velocity or pressure gradient at some level, etc.) must be determined. Much of the work of circulation dynamicists is directed to determining how air-sea transfers generate and distribute the barotropic and baroclinic pressure gradients. To monitor geostrophic circulation there are several choices: (1) monitor sea surface height and interior density fields; (2) monitor the pertinent forces and calculate the fields in (1) with a proven model; or (3) make a hybrid of (1) and (2).

Almost all of the circulation is provided by the surface Ekman (plus probably the bottom Ekman component on continental shelves) and geostrophic components, *except* in intense (inertial) jets or transient flows, on the frictional scale of fronts, in so-called gravitational circulations in estuaries, etc. Many complicating factors enter when we try to account for the development of the density field and circulation, and the circulation's structure and distribution, especially over variable bottom topography.

The net effects of transient circulation on biological processes may be of much significance. For example, though the transient circulation is oscillatory, it is unlikely to be perfectly periodic and so a net displacement will be sustained by a water parcel. Even if it is perfectly periodic, the biological properties of the parcel are likely to change over a cycle of transient circulation due to changes in its physical and biological environs. The latter possibility raises interest in the average covariation, $\overline{\vec{v}'\phi'}$, of fluctuation velocity, $\vec{v}'$, and fluctuation concentration, ϕ', of some biological or chemical property. The divergence of $\overline{\vec{v}'\phi'}$ determines the net effects of so-called eddy transports. The cospectrum of $\overline{\vec{v}'\phi'}$, and its divergence, would reveal the physically dominant scales and processes affecting the biota. In some cases there may

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Space-time conversion involves converting a time series of data into a spatial series with use of the translational velocity of a propagating phenomenon.

be a strong correlation between a biologically important variable, such as dissolved oxygen or nitrate, and a physical variable such as temperature or salinity which can then be used to convert a time series of the physical variable to that of the chemical variable in order to estimate the eddy transport of interest.

Circulation Phenomena

It will help to consider some of the phenomenological elements of oceanic circulation. The oceanic gyres are basic elements of the general circulation (see Worthington, 1976). These gyres have zonal dimensions of the order of 10,000 km and meridional dimensions of the order of 2,000 km. The mid-latitude gyres are marked with narrow, deep, and strong western boundary currents and with broad, shallow, and weak eastern boundary currents. They provide transport routes to link intra- and inter-continental biological communities. The boundary currents generally have associated undercurrents and countercurrents, which provide further feedback mechanisms for the biota. The general circulation gyres are driven by the winds and thermohaline processes and are partially described by the magnitude and distribution of the wind-stress curl (Stommel, 1966). With variable depth, the total transport, $\vec{M} = (M_x, M_y)$, is found from a depth-integrated vorticity equation such as the following:

$$M_x \partial_x \left(\frac{f}{D}\right) + M_y \partial_y \left(\frac{f}{D}\right) = \frac{1}{\rho_o D} (\nabla \times \vec{\tau}_w)_v + \frac{1}{D^2} (\partial_y D \partial_x \chi - \partial_x D \partial_y \chi), \text{ where } \chi = -\frac{1}{\rho_o} \int_{-D}^{o} z \rho g d z .$$

The first term on the right is the familiar wind-stress curl, while the second is the so-called J-bar term, which involves the interaction of the flow with bottom topography and which vanishes if the depth-integrated flow parallels depth contours. The J-bar term can be the dominant term in regimes such as the Gulf Stream, which places priority on the accurate determination of the distribution of the mean density relative to depth contours. Both wind-driven and thermohaline processes affect the distribution of density and determine χ. The vorticity equation is solved for $\vec{M}$ by integrating along f/D contours from a boundary where $\vec{M}$ is specified. The circulation in the gyres seem to have an annual cycle, and to have interannual variability, as does the wind-stress curl field, but not much has been done to quantify their covariations (Niiler and Richardson, 1973). Though basically wind-driven, the gyres are modified by seasonal heating and cooling. The wintertime formation of so-called 18°C water along the Gulf Stream front, and its subsequent sinking and spreading to the Sargasso Sea, is a case in point (Worthington, 1972). Geochemical tracers are finding new uses in general circulation studies to estimate some of the difficult to determine transport routes and transfer rates associated with such thermohaline aspects of circulation (Veronis, 1977).

The western boundary currents separate from the continental margin near the latitude of the maximum wind-stress curl. Upstream of the separation points, the currents have substantial low-frequency variability (Niiler, 1975). Downstream of these separation points, the western boundary currents undergo an amplified meandering process (Hansen, 1970). Some of these meanders develop to the point where cyclogenesis and anticyclogenesis occur (Saunders, 1971; Gotthardt and Potocsky, 1974). Cyclogenesis leads to the southward transfer of a relatively cold water mass with cyclonic vorticity (anticlockwise rotation in the Northern Hemisphere). Anticyclogenesis leads to the northward transfer of a relatively warm water mass with anticyclonic vorticity (clockwise rotation in the Northern Hemisphere). These cold and warm core eddies, of course, transfer biota across the western boundary currents. The meandering, cyclogenesis, and anticyclogenesis processes are not well understood. They may be due to barotropic, baroclinic, or mixed instabilities of these currents. Some progress has been made in explaining meander patterns with the concept of potential vorticity conservation (Robinson et al., 1974; Luyten and Robinson, 1974). Among the determinants of meander patterns are bottom topography and departure angle from Cape Hatteras. There is interannual variability in the number of eddies generated, a fact which begs investigation to see if it is related to interannual variations in the large-scale atmospheric circulation. Frequently, the eddies do not entirely decay in the open ocean. For example, cyclones travel southwestward to be reabsorbed by the Gulf Stream off the South Atlantic Bight. Similarly, anticyclones travel westward, strike the Scotian Shelf or Georges Bank and move southwestward along the shelfbreak until reabsorbed in the Gulf Stream off Cape Hatteras; these anticyclonic eddies are believed to be effective in entraining shelf waters. The biotic feedback possibilities afforded by these eddies are rich and not yet fully interpreted.

The general circulation on the continental shelf and slope off the northeast United States is only roughly known (Bigelow, 1933; Iselin, 1939; and Bumpus, 1973). In the briefest of terms, the flow is ca. 5 cm/s, equatorward, and the net equivalent transport is ca. 1 x $10^6 m^3/s$. This result has been inferred from surface and seabed drifters by Bumpus (1973), and is substantiated by the few existing direct current measurements (Beardsley et al., 1976) and some Cesium 137 and salinity data applied to a box model (Garfield, 1977). Bush and Kupferman (personal communication) obtained similar results through heat budget and box model estimates. However, cautious interpretation is in order because the direction of the surface circulation can reverse (Bumpus, 1967). The seasonal hydrography of the New York Bight has been described by Bowman and Wunderlich (1976). The buoyancy flux provided by river runoff (Ketchum and Keen, 1955) produces a thermohaline circulation component. Wright and Parker (1976) gave a water mass climatology. This limited knowledge of the circulation off the northeast United States contrasts with that off the Pacific Northwest Coast, where direct current and hydrographic measurements have been made over many summers and some winters in the past dozen years. (These modern measurements extend substantially the knowledge of shelf circulation achieved by the pioneering work of Marmer, 1926). There, the annual circulation cycle has been partially documented and related to seasonal, large-scale atmospheric forcing (Huyer et al., 1975; Huyer, 1977; and Huyer and Smith, 1978). In recent years, however, the New York Bight area has been under intensive observational study by NOAA's Marine Ecosystem Analysis (MESA) Program. Though MESA's objectives are site specific and applied to ocean disposal problems, its results will advance our understanding of shelf circulation in the Middle Atlantic Bight.

Our knowledge of the circulation off the southeast United States is even more sketchy, though coordinated direct current and hydrographic measurement programs initiated in the past two years at the University of Miami, Nova University, North Carolina State University, University of North Carolina, and Skidaway Institute of Oceanography promise to improve the situation. The inferential knowledge is documented in Bumpus (1955, 1973) and Stefansson et al. (1971). Overall there is a southward drift, but there are seasonal and local reversals.

For the Scotian Shelf, a summary of early indirect and recent direct circulation studies exists (Smith et al., 1978). (By the way, this study appears to be the first comprehensive synthesis of circulation information and interpretation for all space and time scales examined on the continental shelf for a particular region.) On the average there is a southwest drift, but with biologically significant transfers across the front at the edge of the shelf. The most advanced shelfbreak dynamics study to date, conducted over 18 months, is now under analysis at the Bedford Institute of Oceanography. For Georges Bank and the Gulf of Maine, Bumpus (1960, 1976) summarized the general and tidal circulation information. Though vertically and seasonally dependent, the basic circulation pattern has a cyclonic gyre in the Gulf of Maine and an anticyclonic gyre over Georges Bank. The shelfbreak front around Georges Bank is partially governed by strong tidal mixing in the shoal water atop the Bank. However, the front on the southern side of the Bank is part of the shelf water/slope water front which occurs off the northeast United States. Governed by storms, tides, and possibly offshore eddies, shelf and slope waters apparently surge in and out of the Gulf of Maine through Northeast and Great South Channels. The Gulf of Maine and Georges Bank are now under intensive study, including direct current measurements, by the EG & G Co., U.S. Geological Survey, University of New Hampshire, Woods Hole Oceanographic Institution, and National Marine Fisheries Service.

Air-sea exchanges of momentum, heat, moisture, CO_2, O_2, other gases, aerosols, etc., are largely governed by processes in the upper layer of the ocean. The upper layer is generally characterized by a well-mixed layer extending to the sea surface, and a seasonal thermocline which caps the weaker stratification of the oceanic interior. The upper layer may extend to above or below the base of the euphotic zone; hence, it serves as an oceanic nursery and feeding ground. The surface mixed-layer depth is a strong function of geographical position and season. Because great quantities of heat are stored in the upper layer, and in a form available for air-sea exchange, the dynamics of the upper layer are important to the global climate, OTEC* prospects, and ASW** tactics. For these

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**OTEC: Ocean Thermal Energy Conversion.*

***ASW: Antisubmarine Warfare.*

reasons, observational and theoretical studies of the upper layer have been greatly intensified in recent years (see Pollard, 1970, 1977; Price et al., 1978; Niiler and Kraus, 1977). These studies, through demonstration of a reasonable agreement between model simulations and observations, are providing confidence that the elements of wind-mixing in the upper layer are beginning to be understood within a dynamic framework and to the level of prediction. The biological implications of the new understanding of turbulent entrainment (of interior waters into the upper layer) induced by individual storms have not yet been vigorously pursued. The fact that the seasonal march of the upper layer can be viewed as the cumulative response to the succession of individual storms is to be appreciated. The upper-layer response realized at a particular point is sensitive to the size, shape, strength, type (cyclone, cold front, etc.), and propagation velocity of a storm. These perceptions assist in appreciating the geographical, seasonal, and interannual variability of the upper layer in terms of corresponding variability in storm patterns, which in turn are linked to changes in the large-scale atmospheric circulation.

The upper-layer models and studies referred to above are of a one-dimensional nature, i.e., where horizontal variations are not of dominant dynamic importance. Perhaps of even greater significance to biological and fisheries concerns are two- and three-dimensional regimes (see O'Brien et al., 1977). These regimes include oceanic fronts, sea-breeze systems, and coastal and open ocean upwelling. Oceanic fronts at the sea surface are pertinent because their convergent circulation fields provide a concentrating mechanism for prey and predator alike *and* a localized rupture of the seasonal thermocline which can establish an efficient transport route from the sea surface to the oceanic interior, and vice versa. Sea-breeze systems are pertinent because they can provide an intense air-sea coupling of advection and mixing in nearshore areas on a time scale (1 day) and space scale (50 km), to which phytoplankton can respond. Coastal and open ocean upwelling are of obvious pertinence because of their injection, through advection, of nutrient-rich waters into the upper layer. Off the northeast United States there are oceanic fronts associated with the Gulf Stream, the shelf water/slope water boundary along the shelfbreak, and in the nearshore zone due to riverine and estuarine buoyant discharges. (For a state of the art summary for coastal ocean fronts, see Bowman and Esaias, 1978). All these fronts have somewhat different scales and other kinematic and dynamic properties. Along the United States East Coast, a diurnal sea-breeze system occurs, especially in summertime, as does coastal upwelling.

It may help to realize that one of the properties which distinguishes a continental shelf from the open ocean is that it is all "upper layer" except as modified by the dynamics of the bottom friction layer. Furthermore, it is at least a two-dimensional (i.e., with vertical and cross-shelf variations) upper layer. These notions help to explain why shelf circulation is so much more responsive to atmospheric disturbances than is oceanic circulation. Climatological summaries of air-sea transfers in the North Atlantic by Bunker (1976) and Bunker and Worthington (1976) are adequate for the open ocean and provide coverage but not full resolution for the shelf regions.

The shelf water/slope water front is a persistent feature from Nova Scotia to Cape Hatteras, where it merges with the Gulf Stream front. From Georges Bank southwest, it is largely topographically locked to the shelfbreak (Wright, 1976). It does undergo a strong seasonal modulation: it is a thermohaline front from surface to bottom in winter, and mainly a haline front nearsurface, but still thermohaline nearbottom, in summer (Beardsley and Flagg, 1976). In summer, it is the seaward boundary of the nearbottom "cold pool," which is presumably formed the previous winter* and advected southwestward, drawing initially from local sources and progressively from the Gulf of Maine and beyond (Ketchum and Corwin, 1964). This front is a region of intense transfer by fine scale processes (Voorhis et al., 1976). Much significance can be inferred from the fact that fishing activity is concentrated along the shelfbreak front (see Grant and Rygh, 1973).

From a two-year time series of weekly oceanic surface synoptic charts derived from satellite and other sources, Halliwell and Mooers (1978) have established some correlation between the fluctuations of the position of the shelf water/slope water front and those of the position of the Gulf Stream front, and fluctuations of the wind stress. On kinematic grounds alone, these results are not surprising, and they do suggest that causal mechanisms

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**Brown and Beardsley (1978) documented the wintertime cooling and water mass formation process in the Gulf of Maine.*

can be established for some significant fraction of the variable circulation over the Middle Atlantic Shelf and Slope regime. The two fronts have similar statistics: correlation time of 2 weeks, alongfront correlation distance of 80 km, and a cross-front RMS displacement of 10 to 25 km, increasing away from Cape Hatteras. Such studies help to characterize the variability of an environment important to fisheries and to define sampling requirements for monitoring.

Warm-core, anticyclonic eddies shed by the Gulf Stream drift northwestward to the Scotian Shelf and Georges Bank. From there they drift southwestward along the upper continental slope. As they propagate, they perturb the shelf water/slope water front and presumably entrain shelf water through the front and extrude slope/Gulf Stream water onto the shelf (Morgan and Bishop, 1977; Mooers et al., 1978).

On continental shelves, the transient circulation on the several-day to several-week time scale is generally an order of magnitude greater than the mean circulation. It is thought to be largely generated by atmospheric storms and possibly oceanic eddies. (On the continental slope off New England, Schmitz, 1974, has shown several-week motions oriented along isobaths; these motions could be consistently interpreted as topographically trapped baroclinic waves which had been generated by oceanic barotropic Rossby waves.) The role of transient circulation in the general circulation is not well understood, but it would be surprising if it were negligible. For dispersal of biological, chemical, and geological materials, the transient circulation can be crucial due to the magnitude of its alongshelf displacements (ca. 10 to 100 km) and the matching of its time scales to growth and decay time scales.

The Gulf Stream is a dynamic, downstream boundary for the shelf and slope water off the northeast United States. As such, the Stream entrains shelf water, possibly at a sufficiently great rate to account for the bulk of the circulation sink (Ford et al., 1952; Fisher, 1972; and Kupferman and Garfield, 1977). Other than that the entrained shelf water forms a narrow, nearsurface ribbon of relatively fresh water in the Gulf Stream front, not much is known about this entrainment process. Considering the meandering of the Stream and the vagaries of the weather, it is unlikely that this process is steady. Consistent with that notion are reports of episodic exchanges around Cape Hatteras and between the Middle Atlantic and South Atlantic Bights (Gray and Cerame-Vivas, 1963). These exchanges also involve nonindigenous biota, and they seem to be caused by certain storm conditions. Because the Gulf Stream is normally so close to shore at Cape Hatteras, this must mean that the Stream is displaced offshore when these exchanges occur. If the time of occurrence of these episodes is favorable on the annual cycle, the Carolinian estuaries are seeded with mussel larvae which can develop to maturity and be harvested.

Coastal upwelling is a familiar process at low and mid-latitudes on the west coast of continents, especially on the seasonal time scale. There is a strikingly direct relationship between monthly averaged offshore Ekman transport (equatorward wind stress) and cool anomalies in coastal sea surface temperature (see Wooster et al., 1976). Seasonal coastal upwelling is not as predominant on the East Coast as on the West Coast of the United States, but it does occur for about two months in mid-summer (Taylor and Stewart, 1958; Wells and Gray, 1960). Transient coastal upwelling occurs on the so-called event or several-day time scale associated with the weather cycle. This is perhaps the most significant aspect of coastal upwelling documented on the west coast of continents, and understood to some degree, in the past decade (Smith, 1974). A result of transient coastal upwelling is the delivery of a burst of nutrient-rich waters to the upper layer for a few days every 10 days or so. These are time scales on which phytoplankton and zooplankton can respond strongly. Because the upwelling occurs in a narrow coastal strip of the order of a baroclinic radius of deformation ($L_1 \approx 15$ to 30 km) in width, and because there are mesoscale structures such as fronts and internal tides, mechanisms exist to produce biological patchiness, both temporal and spatial. Transient coastal upwelling on the East Coast has been documented by Brooks and Mooers (1977), Mooers and Brooks (1977), Blanton (1971), and Boicourt and Hacker (1976).

Further strong evidence for the response to transient winds of the Florida Current was provided by Duing et al. (1977) and Lee and Mooers (1977); of the Middle Atlantic Shelf by Beardsley and Butman (1974) and Beardsley et al. (1977); and for nearshore waters ("the coastal boundary layer") by Scott and Csanady (1976).

Part of the response of the continental shelf and slope regimes to forcing of all kinds, but especially wind-forcing, involves their free modes, the so-called coastally trapped waves (Gill and Clarke, 1974; Gill and Schumann, 1974; Wang and Mooers, 1976; and Le Blond and Mysak, 1977). These waves are under the dynamic influence of the earth's rotation (Coriolis parameter), variable topography (bottom slope), and density stratification (static stability). Coastally trapped waves are a fourfold generalization of barotropic and baroclinic, topographic Rossby and Kelvin waves; as such, they are primarily manifested as vorticity or circulation waves with a relatively weak but detectable (ca. 1 to 100 cm) manifestation in sea level. They have time scales of several days to several weeks, alongshore scales of less than 100 to greater than 1,000 km, and equatorward phase propagation (ca. 1 m/s) on the east coasts of continents and poleward on their west coasts. The waves have a high frequency cutoff (less than the Coriolis parameter) and are thus dispersive. Consequently, the long (short) waves propagate energy in the same (opposite) direction as phase. Hence, observationalists and modelers alike must be conscious of these propagating circulation disturbances which may have a distant source. A beneficial corollary is that the existence and properties of these waves can provide substantial alongshore coherence to the transient flow, and thus a basis for prediction from upstream conditions.

The existence and observed properties of coastally trapped waves, especially their relation to wind-forcing, have been documented in several studies of the West Coast; for recent examples, see Wang and Mooers (1976) and Huyer et al. (1975a). A few reported studies exist for the East Coast: Mysak and Hamon (1969) for the Carolinas and Brooks and Mooers (1977) for the Florida Straits.

New studies are in progress for the southeast United States by Brooks (personal communication) and northeast United States and Nova Scotia by Wang (personal communication). While there is evidence for propagating, coastally trapped waves off the East Coast, the situation is complicated by interactive effects with the Gulf Stream off the South Atlantic Bight, and by frictional effects associated with the broad, irregular shelf off the Middle Atlantic Bight and Gulf of Maine. These new analyses are attempting to bring the East Coast studies into line with those on the West Coast of the same genre by using the same methods of analysis. There are some additional points to be appreciated. First, the so-called coastally trapped waves are statistically coherent over an alongshore distance of the order of an alongshore wavelength, which suggests that they have a turbulent eddy character but are constrained by wave dynamics. Second, since their alongshore velocity component is largely geostrophic, and since their offshore trapping scale is of the order of the shelf width or internal radius of deformation, coastal sea level and alongshore velocity fluctuations are strongly correlated. In turn, through the mechanism of offshore surface Ekman transport, sea level and alongshore wind-stress fluctuations are highly correlated. Hence, a dynamically and statistically sound basis exists for predicting a significant fraction of the fluctuating alongshore velocity from a network of coastal sea level and meteorological stations. When combined with data from a few offshore meteorological and oceanographic buoys, and with remotely sensed data (from satellites, aircraft, over-the-horizon radars, etc.) of sea surface temperature, color, height, roughness, etc., the prediction of shelf circulation should now be technologically feasible, and possible within a sound dynamic framework.

Pursuing similar lines of investigation, Wang and Elliott (1978), Elliott (1978), and Wang (1979) have investigated the storm-time scale response of the Potomac River and Chesapeake Bay, respectively. The nature and magnitude of this response is frequency-dependent and largely spatially coherent. At some frequencies, there is a resonant modal response. At others there is a locally forced (off resonance) response or an offshore forced response, which is indicative of coupling to disturbances generated over the continental shelf. Qualitatively similar results have been reported for Narragansett (Weisberg, 1976) and Delaware Bays (Martin, 1978). Therefore, for the relatively large estuaries of the northeast United States, there is a strong response to atmospheric forcing and a coupling with shelf water on the storm-time scale. This largely overlooked aspect of estuarine circulation dynamics, which have been focused on seasonally averaged and tidal circulation, may be of considerable significance to fisheries recruitment, water quality, etc.

Tidal plumes, jets, and fronts in estuaries and at their mouths are another newly appreciated feature of estuarine and riverine dynamics (Garvine, 1974, 1977a, and 1977b). The existence of these features means that there is considerable lateral structure in estuarine circulation and that concentrated transports occur in very narrow bands (Sick et al., 1978).

Finally, there are the tides themselves and their circulation. As has been intimated above, and in the sequel, tidal currents can play a major role in bottom-stirring processes as well as providing substantial transient and, in some cases, net transports. Georges Bank is an area where tidal circulation is one of the dominant components. Redfield (1978) summarized the tides on the shelf of the northeast United States.

In summary, then, many of the physical mechanisms and processes, important to circulation and exchange and presumably to fisheries, have been identified and are partially understood. Less well understood is how they interact with one another, and to what extent they vary from year to year due to variations in the atmospheric circulation.

A Case Study: New Jersey Anoxia, Summer of 1976

An anoxia event occurred off New Jersey in the summer of 1976. It was widely publicized, often as a fish kill. Immediately, various private and public interests set upon pinning the blame on man or nature. In some minds, high shellfish mortalities in the vicinity of disposal sites for various wastes from the United States megalopolis provided striking circumstantial evidence for an anthropogenic cause. Envisioned were fatal effects due to the introduction of toxic materials and the reduction in dissolved oxygen levels associated with the increased biological demands induced by the nutrient loads of the sewage sludge. Yet, others noted anomalous environmental conditions. Though anoxic conditions are occasionally found in continental shelf regions, such as off Peru in 1976 (Dugdale et al., 1977), they have previously been of natural origin. (However, anoxic conditions of anthropogenic cause do occur in semi-enclosed bodies of water, such as estuaries and seas.) Hence, the summer of 1976 anoxia event off New Jersey may have been the first such event on a continental shelf with an anthropogenic cause. NOAA's MESA Program's New York Bight Project had been conducting environmental studies for ocean dump site selections in the Bight since the early 1970s. Thus, though the MESA Program had not been focused on anoxia events, many of the appropriate monitoring and research projects were in progress by the summer of 1976. Over the past two years, NOAA's investigators have compiled a monograph (Sindermann and Swanson, 1978) which analyzes the summer of 1976 anoxia event. This monograph describes a process of concern to the Climate and Fisheries Workshop, and serves as a model (not necessarily ideal but contemporary) for research and monitoring strategies. Because the authors of the monograph had to work with incomplete evidence, their overall results can be interpreted variously. In other words, some controversy attends the analysis of the event, including its significance to the fisheries.

From the monograph of Sindermann and Swanson (1978) a partial scenario is extracted (Mayer et al., 1978; Hazelworth and Cummings, 1978; and Han et al., 1978) and presented below. After a severely cold December and January, there was an early spring. Atmospheric warming produced thermal stratification plus snow melt and river runoff, and thus salinity and enhanced density stratification about a month earlier than normal. An intense and persistent bloom of *Ceratium tripos* in the region may have been "supported" by this early, intense density stratification, and its eventual decomposition could be expected to contribute to reduction of the dissolved oxygen concentration in the lower layer. (Here "supported" is a *double-entendre.* First, the strong density stratification physically supported the *Ceratium*; second, it provided a physical niche they could exploit and monopolize to outcompete other phytoplankton for light and nutrients.) The anomalously early stratification obviously eliminated ventilation of the lower layer by free convection.* Associated with the early atmospheric warming was an early cessation of the wintertime weather cycle of vigorous cold fronts and cyclones. This could be expected to reduce the amount of forced convection** produced by wind-stirring of the upper layer. Other factors came into play with the shift in the weather cycle. In early summer, a several-week period of weak *but* persistent winds with a poleward component occurred off New Jersey, driving coastal upwelling. Associated with the upwelling was an onwelling (onshore flow of lower layer water) of nutrient-rich and oxygenated water from the outer shelf to the inner shelf. During this period, the dissolved

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**In this case, free convection is overtuning due to a negative buoyancy flux (cooling or evaporation) at the sea surface.*

***In this case, forced convection is mechanical stirring due to wind-generated waves and turbulence in the upper layer. Tidal motion can play a similar role in stirring the bottom layer.*

oxygen concentration in the lower layer decreased at an anomalously high rate and reached a level much lower than the usual late-summer minimum. About that time, the shellfish mortality telltales of the anoxia event began to be reported by skin-divers and fishermen.

Of considerable interest is that Han et al. (1978) used a diagnostic model, discussed further below, to hindcast the several-week average circulation in the New York Bight, with special emphasis on the lower layer. The model requires an estimate of the hydrographic and surface wind fields in the domain of interest, and of the horizontal velocity along the boundaries of the domain. Off New Jersey, they found a convergence of flow in the lower layer, including from offshore. A consequence of this shoreward flow was an appreciable advection of dissolved oxygen into the anoxic area, which led to the conclusion that *twice* as much oxygen had been consumed as had been estimated from a static, apparent viewpoint. It was also concluded that the onshore flow in the lower layer had probably served to concentrate *Ceratium tripos* in the nearshore, anoxic zone, increasing further the biological demand for oxygen.

Late in the summer, Hurricane Belle passed over the anoxic region. This hurricane generated vigorous inertial oscillations and some wind-stirring, but it did not overturn the water column, and the stratification quickly "healed," leaving the ventilation of the lower layer to the normal autumnal cooling. Since Hurricane Belle was small, weak, and swift, the Bight's response may not have been representative of its response to hurricanes in general.

The scenario for the New Jersey anoxia event, summer of 1976, may never be complete, nor the blame correctly and fully apportioned. Yet even if anthropogenic causes played a dominant role, natural causes played a significant role, too. The event itself, the public's reaction, and the scientific community's response probably portend the future. For the physicists, the MESA experience points to our poor knowledge of the normal seasonal cycle of, and departures from, stratification and circulation, and the mechanisms controlling its formation and annihilation. It also demonstrates the promise and utility of at least diagnostic models and the monitoring networks which such models require. Having had some comparable information from previous years proved invaluable for recognizing distinctive features of the regional atmospheric and oceanic systems in 1976; thus, the case for an intelligently designed atmospheric and oceanic monitoring effort and climatology was enhanced.

Present Status of Modeling

Mixed-layer dynamics models were discussed in the "Circulation Phenomena" section. The broad features of the oceanic general circulation have been described most recently in the analytical work of Veronis (1973, 1976, and 1978) and in the numerical models of Holland (1977, 1978). The less than satisfactory treatment of eddy processes in numerical models is a recognized weakness and motivates much of contemporary theoretical and observational investigations in the open ocean (Robinson et al., 1977; Rhines, 1977; Dantzler, 1976, 1977; Rossby et al., 1975). The numerical experiments attempt to account theoretically for the circulation as it is observed to be, to simulate a hypothetical case in order to illustrate the adjustment of circulation to a change in applied forces, or to simulate the growth of an instability intrinsic to the circulation.

With contemporary field experiments employing current meter arrays, it is becoming possible to test dynamic balances which can be a precursor of improved model development. Allen and Kundu (1978) provide an inspiring example from the Oregon shelf.

For coastal upwelling regimes, a series of numerical simulations have been conducted by O'Brien and his students (see O'Brien, 1976; O'Brien et al., 1977). These simulation models illustrate the effects of coastline configuration and shelf topography on upwelling circulation. Hamilton and Rattray (1978) demonstrate the effects of continuous density stratification in a numerical model for coastal upwelling. Recently, the onset of an el Niño has been simulated in a large-scale model which includes the equatorial regime (Hurlburt et al., 1976). Larsen and Laevastu (1973) reviewed numerical models of ocean surface currents.

A few steady-state circulation models exist for the Middle Atlantic Bight. Csanady (1976) considered a model composed of surface and bottom Ekman transports plus barotropic and baroclinic geostrophic transports, using a linearized bottom friction law. It can be adjusted to give a circulation pattern consistent with available observations, including a cross-shelf bottom flow with a mid-shelf divergence. Bishop and Overland (1977) employed a similar model. Stommel and Leetmaa (1972) examined a model which allocated a primary role to buoyancy advection and diffusion to relax the nearshore buoyancy anomaly produced by river runoff. These models imposed cross-shelf mass balance, are most applicable to winter, do not do justice to the nearshore or shelfbreak regions, and impose an alongshore barotropic pressure gradient in the final analysis to obtain the correct direction of the alongshelf flow. Considerable controversy prevails over the existence of the alongshore pressure gradient, mechanisms for its maintenance, and its consequences for shelf circulation (see Sturges, 1974). The possible alongshore pressure gradient could be expected to vary on climatic time scales and to consequently vary the circulation over the shelf and slope. To document and understand this pressure gradient is a high-priority item. (Some alongshore dependence is included by Csanady, 1978, and the barotropic response of the Gulf of Maine was examined by Csanady, 1974.)

Numerical modeling for the Middle Atlantic Bight region is in its early stages. A. Tingle of Brookhaven National Laboratory is working on a barotropic model. As described in the section by Rasmusson and Williams, A. Blumberg and G. Mellor of GFDL are developing a multi-level model with high resolution over the continental shelf. They use a computational scheme which separates barotropic and baroclinic modes of motion and achieves considerable economy in so doing. In all these limited area models, open boundary conditions comprise one of the thorniest challenges; Heburn (1977) provided an annotated bibliography on the subject.

Heaps and Jones (1977) reported on the numerical integration of a three-dimensional shallow sea model. By introducing vertical eigenvalues and eigenfunctions, they reduce the dimensions to two for the numerical calculations. They assume a density field and impose wind and atmospheric pressure fields. This type of model effectively simulates some aspects of the circulation response to variations in inputs, producing information on the sensitivity of model solutions to model inputs (data, parameters, and assumptions).

A more tightly constrained model is the Hsueh/Galt diagnostic model, applied to the New York Bight by Han et al. (1978). It has imposed density, sea surface height (adjusted with the aid of current measurements to satisfy mass conservation), and wind-stress (single-point) fields. The model addresses a steady state, which means the time scale must be a week or longer.

Analytical models for specific processes continue to be developed. Beardsley and Hunt (1978) have examined one- and two-layered models for estuarine outflow on to the shelf, taking into account the earth's rotation, stratification, variable depth, and turbulent diffusion. In the Northern Hemisphere, the outflow turns to the right in a single-layer model; in a two-layer model, the outflow turns to the left in the upper layer, while the inflow comes from the right in the lower layer. Answers to such questions may be crucial to the understanding of shelf-estuarine ecosystem interactions, which involve the dispersal of larvae and the recruitment of juveniles, and the dispersion of nutrients and dissolved and particulate pollutants.

Another example of a process model is given by Csanady (1978) for the geostrophic adjustment of a surface-to-bottom front to a wind-stress impulse. With some generalization and testing, this model may provide the basis for inferring alongshore transport fluctuations on the shelf produced by Ekman transport variations, and associated with fluctuations in the locus of the shelf water/slope water surface thermal front as monitored by satellite IR.

In summary, the outlook is good for the further development of conceptual, analytical, and numerical models of circulation and exchange processes which have some bearing on the climate and fisheries problems. A challenging task is that of applying the circulation modeling results to fisheries problems. For this, biological submodels may be required in some cases; in others, simply having people available who are knowledgeable in fisheries oceanography to interpret the modeling implications for fisheries will suffice.

Strategies for Circulation Monitoring and Prediction

It is certain that development of seasonal circulation models for climate and fisheries in the extended jurisdiction zone will require lengthy time series of several variables sampled at several locations. Historically, there are records of surface weather elements, sea level, and sea temperatures (and, in some cases, salinities) in coastal areas which are at least a few decades in length. There also exists a significant—though randomly sampled, aliased, and biased—hydrographic data base, which developed mainly between 1930 and 1960. For the future, the availability of the monitoring data base should not be taken for granted. Such monitoring efforts can be expensive, hard to defend, and, thus, easy to eliminate for reasons of false economy. On the other hand, the scientific community has not made a strong case for monitoring through thorough analysis of existing observations, *nor* has it made a scientific investigation of the necessary and sufficient coherent monitoring network for some stated purposes. For example, experiments to define space-time-variable sampling requirements for some monitoring objectives are not usually done before a monitoring program is established. In the near future, monitoring capabilities may be enormously improved because of rapid technological advances in data sensing, logging, and telemetry. For example, even though weatherships and lightships are being abandoned, the NOAA Data Buoy Office (NDBO) now has several telemetering meteorological and oceanographic buoys operating on the continental shelf, and further offshore, of the United States Atlantic coast. Satellites provide increasingly frequent and dense coverage of the sea surface with IR and visible imagery, radar altimetry, and, soon, further active microwave products. These technologies open new possibilities for scientific inquiry and monitoring*, but they are not full replacements for the older methods, *nor* are they being driven by a scientific program. From modern sampling theory, theories of oceanic dynamics, and understanding of coastal ecosystems, a scientifically designed monitoring program should be possible, one that provides valid information on large-scale phenomena and other suitable inputs to diagnostic or prognostic models. Monitoring programs do not preclude the necessity of process experiments; as a matter of fact, they enhance, and in turn are improved by, such experiments. However, they do compete for resources, and the required institutional arrangements are different.

A major reason why the status of monitoring is so dismal, and why the data base is so underexercised, is that the data archives have not kept pace with present and future realities of investigation. In other words, the value of the data base resource is only partially recognized, and the importance of rendering it in a convenient, complete, and certified fashion is not broadly appreciated. For example, coastal tide gauges are mainly seen as tide sensors by the National Ocean Survey (NOS) rather than as part of an ocean dynamics array for sea height (level) determination; accordingly, the data are processed, if at all, by archaic methods, and key stations are abandoned.

In thinking about monitoring, there are many generic questions to be considered. For example, one does not want much more data than are necessary to define a process. This means that stations should not be redundantly close in space or samples redundantly close in time, and highly correlated variables need not be sampled. Conversely, at least some observations need to be made across the largest dimensions of the spatial domain of concern, over several cycles of the longest time scale known to be of great significance, and across "variable space"—from winds to sea levels to phytoplankton to fish. Obviously, there is great merit, and potential predictive power, in developing a hierarchy of statistical correlations between observational fields *if* a theoretical basis for causality is also established. Which then brings one around to considering predictive models, and their needs for initial and boundary condition and verification data, in defining monitoring requirements, a topic further explored below.

To tentatively summarize, it is known that the extended jurisdiction zone off the northeast United States responds to: (1) air-sea transfers, such as wind stress and heat transfers; (2) offshore influences, such as Gulf Stream meanders and eddies; (3) onshore influences, such as river runoff; and (4) upstream and downstream influences, such as variations in wintertime cooling of the Gulf of Maine in the water mass source region and in Gulf Stream entrainment of shelf water in the water mass sink region. For (1), much can be inferred from coastal and offshore wind and air temperature records plus sea levels and coastal temperature. For (2), much can be inferred from satellite passive and active systems. For (3), much can be inferred from stream gauges and ART* flights. For (4), new strategies are required. That is not to say that the dynamic relationships for (1), (2), and (3) could not do with a good deal of additional development as well.

Here, the term prediction is used in its broadest sense; it includes hindcasts as well as forecasts. Thus, prediction includes any scientific attempt to infer more than has actually been measured. Inter-

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**See Huang et al. (1978) for the first use of satellite radar altimetric measurements of sea surface height to study the variability of the Gulf Stream and mid-ocean eddies.*

**ART: airborne radiation thermometer.*

polation is a good example of a hindcast, while extrapolation is a good example of a forecast.

There are several requirements which must be met to achieve a predictive capability for oceanic circulation. One is a good climatology of oceanic circulation and hydrography *and* of atmospheric and other forcing.* A second is a quantitative understanding of causal relationships so that models can be constructed with appropriate parameterizations. A third is the means to determine the boundary and initial conditions, to solve the model, and to evaluate its solutions through verification tests. If a hindcast is being made, then real-time data are nonessential because a diagnostic model is run on the basis of available historical information. If a forecast is being made, then real-time data are vital for initialization of the oceanic prognostic model, determination of the evolving forcing functions, and model verification. The best initialization may be obtained from a combination of data from the climatology, real-time sources, and prior model forecasts. In fact, the climatology will be superior to the predictive model unless the model has "skill." Measures of "skill" and other model specifications—for example, how "good" do the results have to be?—are needed early in the development of a model.

Yet another type is that of simulation models, which may be extremely useful even if they correctly account for only one process. They can give insight into how the process functions and can be adjusted to calibrate the model. And if run for a broad range of conditions, they can provide statistical information on extremes and events as well as a variety of case studies.

An easily overlooked aspect of predictive modeling is the need for an adequate specification of the forcing functions. (There is a real possibility of overreaction—to move from neglect to saturation with forcing information.) Part of the "adequate specification" will be determined by the quality required of the model results; a more fundamental part will be determined by the model's response to idealized forcing. To the extent that the system is linear, the answer is entirely to be found in the linear response function; i.e., the ratio of an output ("solution") variable of the model to an input ("forcing") variable as a function of Fourier coordinates (frequency and wave number). It would not be unheralded to find that the model does not respond much to some time and space scales. Hence, determination of forcing on such scales would not be accorded high priority. This type of analysis also provides a measure of the sensitivity of the model, and presumably of the physical system, to the quality of the forcing data. Not all questions are best formulated in Fourier terms. For example, one may have an idealized model storm, a hurricane or a winter cyclone, with several parameters to describe it. It would be of interest to know once and for all whether you must have the initial position, speed and direction of advance, diameter, maximum winds, minimum pressure, etc., correct to M percent in order to simulate the displacement of a water parcel in the surface Ekman layer during the period of storm influence to within N percent.

While predictive model development progresses in an unpredictable fashion, other items on the agenda must be attended to. The oceanic and atmospheric climatologies must be maintained *and* analyzed. Their adequacies need to be under continuous scrutiny, and opportunities for redesign of routine monitoring efforts based on new technology and scientific knowledge need to be addressed.

To end on a cheerful note, the point will be made that the pathway to prediction may not always be ponderous. As one example, O'Brien et al. (1974) developed a forecast capability for Coho salmon off Oregon. By establishing a relation between the location of Coho salmon and the position and state of the coastal upwelling front, which in turn were related to the surface wind field, a predictive capability was acquired. Then, using weather forecasts, ART data, and a rapid information dissemination system, they were able to predict fishing conditions on a daily basis, enabling fishermen to increase their yield per unit effort. Of course, efficiency in fishing is not always immediately desirable if effective fisheries management mechanisms do not exist to safeguard the stock. Yet, in due course, the safeguards can be provided, and it is desirable to achieve efficiency in any industry.

Another example is provided by Simpson and Pingree (1978). They have studied fronts found in the English Channel and the Celtic and Irish Seas. These fronts occur over shoal topography when and where the tidal-stirring is sufficient to overcome the stabilizing influence of seasonal heating; such

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**The report of Williams, Godshall, and Rasmusson (1977) provides a climatological summary for the Middle Atlantic Bight. Seasonal, or finer, averages of hydrography, surface and bottom drift, surface winds, and other variables are available in a grid over the Bight. Though imperfect, the data base is at least rich enough to provide useful climatologies.*

relationships provide some predictive capability for these fronts per se based on sound physical principles. Because the dominant flow is tidal currents, and thus highly predictable, as is the seasonal heating, a good basis exists for prediction of this class of fronts. The predictive capability is enhanced by the fact that the fronts, as surface thermal fronts, can be detected in satellite IR images, etc. Because the tidal currents are modulated on the monthly spring-and-neap cycle, and because the tidal-stirring depends upon the cube of the tidal current, a strong test of the relationships is provided in the natural setting. The surface distribution of chlorophyll "a" is strongly correlated with the surface distribution of temperature, and, in particular, the locations of chlorophyll "a" maxima correspond well with those of surface fronts. In turn, this means that phytoplankton are concentrated on the stratified side of surface fronts. Presumably, the higher trophic levels take advantage of this concentration of food. (Fronts also concentrate trace elements other than nutrients, which are taken up by primary and secondary producers [Sick et al., 1978].) Studies of vertical sections show that there is a pool of nutrients beneath the thermocline which has been ruptured and uplifted to form the surface fronts. Thus, without the fronts the upper layer is light-rich but nutrient-poor, while the lower layer is nutrient-rich but light-poor. With fronts, the water on the well-mixed side of the front is not particularly productive because it is light-poor though nutrient-rich due to deep stirring. In contrast, on the stratified side of the fronts the water is light-rich due to the shallow, strong thermocline below, and nutrient-rich due to turbulent exchange from the lower layer into the upper layer. These studies not only helped to explain biological patchiness through elucidating physical mechanisms for production of patchy distributions in food, but they also illuminated a process the consequences of which should be immediately transferable to all such environments in the world. One of the lessons is that through combined physical and biological process studies well-defined relationships may be established which can give priority to prediction strategies. In this case, the fronts which produce annoying heterogeneity in chemical and biological fields serve to concentrate food (through convergences) *and* to provide a convenient signature for monitoring and prediction—you predict the presence and strength of the front and "all else" follows from the understanding of the sequence of processes. When further understanding of the relation of these fronts to fisheries is achieved, and when the interannual variability in the seasonal heating is examined, the relation between climate and fisheries may be largely established for this class of environment.

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Brief History and State of the Art of Fish Production Models and Some Applications to Fisheries off the Northeastern United States

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Abstract

Production models applicable to individual fish, cohorts of fish, and entire populations are reviewed. Hypotheses (often untested) describing the relationship between production and the biotic and abiotic environment are advanced. The paper supports the following generalizations:

(1) The effect of the physical environment on fish production is better understood by considering fisheries in an ecological context instead of in the context of the traditional fish production models. On the other hand, fish production models can sometimes be modified to account for environmentally induced fluctuations empirically.

(2) Most of the variability in fish production results from presently unexplained variability in reproductive success. Variability in reproductive success probably reflects a plethora of complex biotic and abiotic interactions of early life stages of fish.

(3) Fish production models do not usually consider the effect of a fluctuating environment explicitly, but their application is usually tempered so that the conclusions based on these models are generally valid and useful.

Introduction

The primary mandate for marine fishery management in the United States is the Fishery Conservation and Management Act of 1976 (Public Law 94-265, 94th Congress, H.R. 200, April 13, 1976). The act defines optimum yield (OY) of a fishery as the amount of fish: (1) which will provide the greatest overall benefit to the nation, with particular reference to food production and recreational opportunities; and (2) which is prescribed as such on the basis of the maximum sustainable yield (MSY) from each fishery as modified by any relevant economic, social, or ecological factors. The concept of maximum sustainable yield has traditionally been interpreted in the context of a single species situated in an environment typical of the long-term average. This narrow interpretation of MSY has led to numerous criticisms of the concept (Larkin, 1977, and Sissenwine, 1977a, for example). The interactions of a fish population with its physical and biological environment (abiotic and biotic interactions, respectively) are ecological factors appropriate for consideration in the determination of OY.

The Climate and Fisheries Workshop addresses the interaction of fish populations with their physical environment. This paper reviews the components of production of fish populations and traditional methods of assessing production. The paper is intended to establish a foundation for further discussion of the relationship of fish production to abiotic factors. It also briefly describes two ecosystem-oriented models intended to support fisheries management of highly productive regions, the North Sea and Bering Sea. Finally, the status of studies of fish production and population dynamics of stocks off the northeastern United States is reviewed. For those unfamiliar with the fisheries of the region, this review will aid in determining if adequate biological information is available for particular models of the relationship between abiotic factors and fish production.

Production by Individual Fish

The productivity of a component of an ecosystem is the rate at which energy is stored in that component as protoplasm. Production by animals (the topic of this paper) results from the transfer of energy stored in the tissue of their food into their own tissue. Thus, animals must eat in order to produce, but the transfer of energy from food to the feeding individual is not 100 percent efficient. Food consumption is related to production by the following equation:

$$k\,C = Q + S + \Delta W \qquad (1)$$

where C is the energy value of food consumed, Q is the energy used for metabolism (body maintenance), S is the energy used for reproductive material, Δ W is the energy value of tissue added by growth, and k is the portion of consumption that is assimilated. The value of k is typically about 0.8 (Parrish, 1975; Davis and Warren, 1971). The unassimilated portion of consumption is primarily eliminated from the body as feces, with a smaller portion excreted in urine. The energy used for metabolism can be further subdivided into: (1) the energy used for maintenance of the resting and unfed animal (standard metabolism), (2) energy used during digestion, and (3) the energy used for activity such as swimming (Davis and Warren, 1971). Production of an individual fish will be defined as Δ W for the purposes of this paper. S is not included in production of mature animals because the energy stored in reproductive material is not permanently incorporated into the animal's tissue. In order to account for the energy value of reproductive material, S is included in the production of the earliest life stage of progeny.

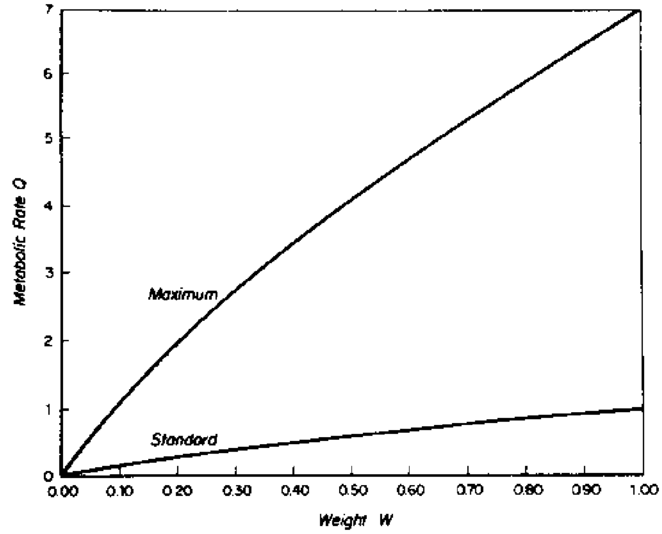

Figure 1. Two hypothetical examples of the functional relationship between the rate of metabolism and body weight, Equation (2). The examples used are those considered by Parrish (1975) as representatives of the maximum (α=7.0) and standard (α=1.0) metabolism of fish. For both examples, γ =0.8.

Parrish (1975) provides a brief review of the scientific literature describing C, S, and Q for an individual fish. Δ W can be calculated by subtraction. Q can be expressed as a power function of body weight, W.

$$Q = \alpha W^{\gamma} \qquad (2)$$

The exponent, γ, is about 0.8 for many fish species (Mann, 1965; Paloheimo and Dickie, 1966; Ursin, 1967). Thus, the amount of energy used for metabolism per unit of body weight decreases as W increases. α is a function of at least temperature and activity level, which is, in turn, closely related to the consumption rate. Examples of Equation (2) are plotted in Figure 1 for two values of α which indicate the range of Q relative to activity level.

S is a function of the weight (W) of the fish. Where food is not limited and a fish receives sufficient nutrition, a simple expression for S is

$$S = u\,W \qquad (3)$$

Parrish indicated that the average value of u reported by several authors was 0.1 for both sexes combined. It is also common for fishery scientists to report the reproductive potential of fish as the number of eggs produced (fecundity) as a function of length (Howell and Kesler, 1977, for example). The relationship between fecundity and length is usually expressed as a power function, with the exponent typically about 3. If the energy content of eggs is independent of length and if the exponent of the fecundity/length function is the same as the exponent of the function relating weight to length, then S can still be related to W as in Equation (3). Data on the energy value of eggs taken from fish of various lengths are seldom available.

Obviously Equation (3) only applies to sexually mature fish. The proportion of mature fish can be determined as a function of both size and age from a sample of fish selected randomly from the population.

Parrish considers three functions relating consumption rate to prey density, P.

$$C = \theta P \tag{4}$$

$$C = (1 - e^{-\theta P})\, C_{max} \tag{5}$$

$$C = \frac{PC_{max}}{\theta + P} \tag{6}$$

C_{max} is the consumption rate when prey density is not limiting and θ is an additional parameter.

Equation (4) is based on the assumption that the consumption rate is proportional to the rate of encounters between predators and prey. The simple proportional relationship between the consumption rate of a single individual and the density of its prey is inherent in early analyses of species interactions by Lotka (1923) and Volterra (1926). According to this equation, an unlimited increase in the concentration of food results in an unlimited increase in consumption. Ivlev (1961) considered this a biological absurdity. He proposed Equation (5) as a realistic alternative to Equation (4). Ivlev assumes that there is a maximum consumption rate and that the slope of the function relating C to P is proportional to the difference between C and C_{max}. Thus, the marginal change in C decreases as P increases. While Equation (5) is usually attributed to Ivlev, the same functional form was also proposed by at least Gause (1934) and Watt (1959).

Holling also rejected Equation (4). He proposed that consumption during an interval of time is proportional to the product of the time available to search for food and the food density. Furthermore, he assumed that the time available for searching is the length of the time interval minus the time spent eating and that the time spent eating is proportional to the actual amount eaten. An equation expressing these assumptions simplifies to Equation (6). Holling (1959) found that Equation (6) explained more variation in consumption rate than Equation (4) or (5) for the data he considered. An example of each of the three feeding functions considered here is plotted in Figure 2. It is important to note that fish consumption is less sensitive to prey density as food becomes more available according to the two biologically acceptable relationships.

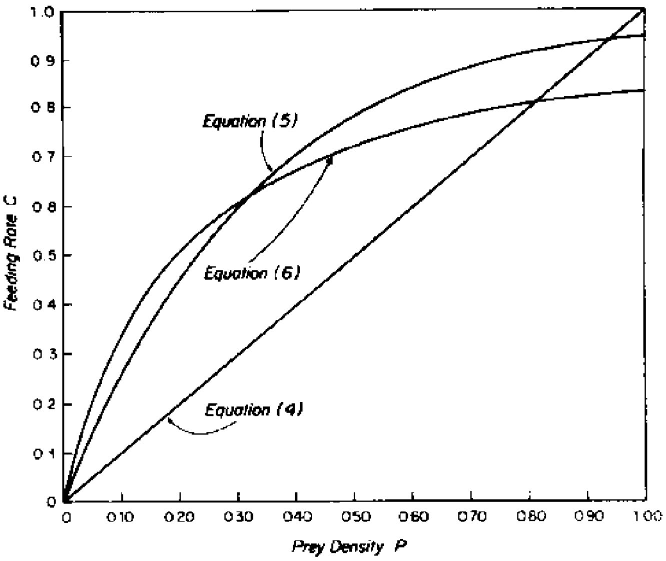

Figure 2. Hypothetical examples of three feeding functions. $C_{max} = 1.0$; $\theta = 1.0, 3.0$, or 0.2 for Equation (4), (5), and (6), respectively.

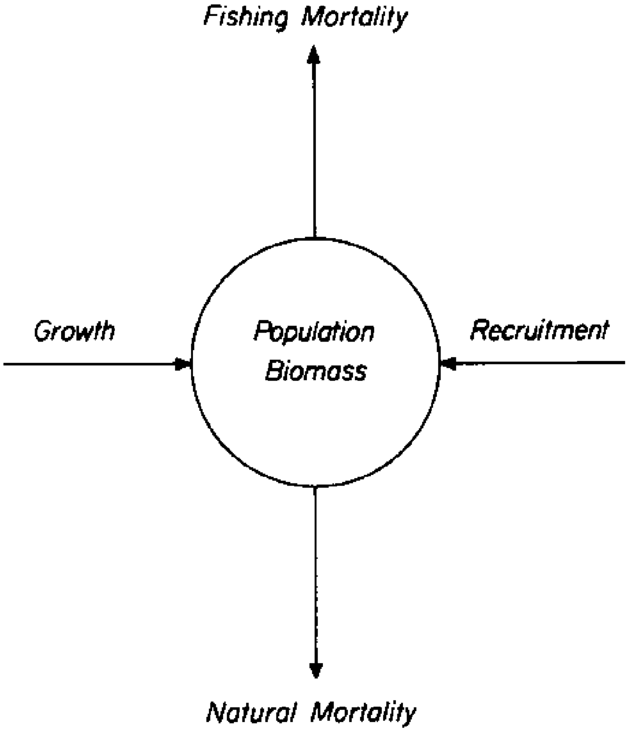

Figure 3. Input-output model of a fish population as suggested by Russell (1931).

Population Production

With the development of both the steam trawler and otter trawl during the nineteenth century, fish stocks of the North Sea showed clear evidence of declining abundance for the first time (Russell-Hunter, 1970). Thus, there was an immediate need for a better understanding of fish production. A good early exposition on the dynamics of exploited populations and the relationship between population production, catch rate, and changes in stock biomass was given by Russell (1931). Russell's model can be represented by Figure 3.

The exploitable biomass (B) is the portion of a fish population which is vulnerable to the fish-catching method. Exploitable biomass is almost always expressed as wet weight of fish tissue, which is approximately proportional to its energy value (usually about 1 kilocalorie per gram wet weight; see data in Daan, 1975, for example). For most fisheries, small fish are not vulnerable and therefore not included in the exploitable biomass. As they age and increase in size they become vulnerable and their weight is added to the weight of the exploitable population. This process is called recruitment. Recruitment is a form of production by the exploitable population. Recruitment is only apparent production because it is the instantaneous transfer of energy from one component of the ecosystem (young fish of a species) to another (exploitable fish of the same species), which is not related to a predator/prey interaction. The apparent production of recruitment is less than the actual total production of prerecruits (by growth) because some prerecruits do not survive until recruitment. Actual production of the exploitable biomass results from growth of individuals in the population, the sum of which is G. On the other side of the ledger, the weight of fish that die as a result of fishing (D_F) or natural causes (any causes other than fishing, D_M) is deducted from B. Therefore

$$\Delta B = R + G - D_M - D_F \qquad (7)$$

From the exploiter's perspective, the production of the population that can be harvested without changing B is $R + G - D_M$, which is usually called surplus production (SP) or equilibrium catch (CE, which equals SP by definition).

The factors that determine SP are related to the production by individual fish as described in Equation (1). Clearly, growth is related to the efficiency of food utilization. While the growth rate of a fish does vary in response to both its biotic and its abiotic environment, for exploited marine fish it is often adequate to empirically relate growth solely to age.

It is possible that the growth response of fish to anomalies in prey density may be buffered by adjusting the proportion of assimilated consumption stored in reproductive material. Thus, when prey density is low, the growth rate of a fish may be maintained at the expense of its reproductive capacity. The extent to which this occurs, if at all, is unknown for most marine fish. It is also possible that food is not generally limited for exploited marine fish and therefore consumption is not sensitive to prey density. This occurs for Equations (5) and (6) at prey densities for which the slope of the function approaches zero. Anomalies in prey density may also be compensated for by changes in metabolic rate.

The natural mortality rate* of marine fish (M) is difficult to estimate. Therefore, the degree of variability in M is virtually unknown. In practice, the natural mortality rate of exploited fish is almost always assumed constant.

The likely natural causes of death of fish are predation, starvation, lethal abiotic conditions, contagious diseases, and noncontagious diseases. Since man tends to exploit species at the higher trophic levels, the predation mortality of exploited fish is likely to be lower than for other components of the ecosystem. This may not be the case in areas where fish-eating marine mammals or large pelagic sharks are abundant or for several small pelagic species (menhaden, for example). On the other hand, the predation mortality of exploitable size cod, haddock, tuna, striped bass, and numerous other species is likely to be low, although the extent of predation by large pelagic sharks or marine mammals is usually unknown. For species which exhibit only modest fluctuations in growth rate of exploitable size individuals, starvation mortality must also be very low, since a starving fish will stop growing. Therefore, for many species it is likely that lethal abiotic conditions and contagious and noncontagious diseases account for most of the natural mortality of fish once they have been recruited into the exploitable population. In some cases, diseases or sublethal abiotic conditions may be the indirect cause of death, while the actual cause of death is either starvation or predation. The mortality rate of fish caused by noncontagious diseases is probably insensitive to both climatic conditions and biotic factors. On the other hand, the death rate caused by contagious diseases is likely to be related to population density as well as to other factors. The death rate resulting from lethal abiotic conditions (temperature, oxygen concentration, salinity, for example) is probably only significant occasionally. Thus, the assumption of a

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**All mortality rates are expressed as instantaneous rates (Ricker, 1975, page 8) in the paper.*

constant natural mortality rate for exploitable fish may be adequate (particularly when F is substantially higher than M) for a large number of species except occasionally during outbreaks of contagious diseases or for extreme abiotic conditions. Unfortunately, the available data base is inadequate to test the validity of these hypotheses for most species.

Recruitment rate (R) of young fish to the exploitable population depends on the biotic potential of the spawning stock that parents each cohort (usually annually; thus, cohorts of fish spawned together are called a year class). R also depends on the survival of fish from spawning until they reach the size or age of recruitment. The survival rate of early life stages of fish (eggs, larvae, and juveniles) is usually assumed to increase with size. There may be a critical size above which mortality rate drops sharply.

Variability in recruitment is the major source of variability in production for most exploited marine fish populations. Variability in recruitment has seldom been adequately explained by consideration of biotic factors alone. Most fishery scientists agree that much of this variability is related (either directly or indirectly) to abiotic factors.

There are numerous possible direct causes of variability in recruitment, including the following:

(1) variability in egg production resulting from variability in the size and age composition of the spawning stock, and/or variability in the egg production per unit of spawning stock;

(2) variability in predation mortality suffered by early life stages;

(3) variability in viability of eggs;

(4) variability in food availability which affects variability in starvation mortality and growth rate which also may affect early life stage survival;

(5) variability in death rate resulting from contagious diseases and, probably to a lesser degree, noncontagious diseases; and

(6) variability in death rate of early life stages resulting from lethal physical or chemical conditions. These potential causes of variability in recruitment are related to intraspecies competition and/or predation, interspecies competition and/or predation and/or the abiotic environment. For example, the survival rate of juveniles may decrease as spawning stock size increases as a result of cannibalism (intraspecies predation; number 2 above); larval survival may decrease when other larval species with similar feeding habits are abundant (interspecies competition; number 4 above); or the survival rate of larval fish may increase when hydrodynamic conditions are favorable for larval retention on preferred nursery grounds (favorable abiotic environment; numbers 2 through 6 above). Fluctuations in the abiotic environment may indirectly be responsible for variability in recruitment related to biotic factors like competition and predation. Cushing (1973) contends that variability in recruitment results from the match or mismatch of the reproductive cycles of a species and the productive cycles of interacting species. The timing between interacting species may be influenced by subtle fluctuations in climate. The indirect effect of climate on recruitment may be magnified by the interaction of early life stages with competitors, predators, or prey. The ecosystem is so complex that the mechanisms responsible for specific fluctuations in recruitment as a function of changing climatic conditions may never be known, although an empirical relationship may be determined. In some cases, the mechanism relating recruitment to abiotic factors may be direct and easily understood. This is most likely when egg and larval survival depend on transportation to or retention in a suitable habitat. In some regions, marine fish production is dependent on estuaries as nursery grounds. This is particularly true for the South Atlantic and Gulf of Mexico. For estuary-dependent species, recruitment may be particularly sensitive to environmental conditions on nursery grounds which may be only a minor portion of the range of the species. Of course, variability in recruitment may be related to a combination of the factors considered above.

Empirical Growth Models

In developing a growth model* for the average fish of a population, Brody (1927, 1945) noted two phases of growth in length: (1) a period of accelerated growth for younger individuals, followed by (2) a period of slower growth, with the animal reaching a maximum size. Equations which describe such growth are

$$\ell = a\, e^{K't} \tag{8}$$

$$\ell = b - ce^{-Kt} \tag{9}$$

where ℓ = length at age t; a, b, and c are con-

**Functional relationships between length and age are traditionally called models of growth or growth functions. In fact, a model of growth is obtained by differentiating with respect to age, dl/dt.*

stants having the dimensions of length; and K′ and K are instantaneous growth-rate coefficients where growth rate is proportional to ℓ and the difference between ℓ and the maximum length of the species for Equations (8) and (9), respectively. For exploited fish populations, Equation (8) is usually ignored, since it usually applies to prerecruit fish only.

Attention is focused on fitting Equation (9) to data. As t increases indefinitely, ℓ approaches b, which will be redefined as L_∞. Then rewriting Equation (9) as follows:

$$L_\infty - \ell = ce^{-Kt} \tag{10}$$

It is clear that the difference between the asymptotic length L_∞ and the current size, ℓ, decreases exponentially at rate K. The difference decreases to one-half in time .693/K.

If, instead of using Equations (8) and (9) to describe the growth of the population, Equation (10) is modified such that $\ell = 0$ at some time t_0, the resultant expression is

$$\ell = L_\infty (1-e^{-K(t-t_0)}) \tag{11}$$

where $t_0 = \frac{1}{K} \log_e (c/b)$ and $c = be^{Kt_0}$. This expression is attributed to von Bertalanffy (1938). Unlike Brody's model the length of a fish can be 0 at some hypothetical time $t_0 < 0$.

The von Bertalanffy function, Equation (11), is the most widely applied growth model by fishery scientists. The popularity of the model probably results in part from its supposed biological justification. Since growth rate depends on the difference between what goes in and what goes out,

$$\frac{dW}{dt} = H_1 W^{2/3} - H_2 W \tag{12}$$

where anabolism (intake) is assumed proportional to the surface area of the gut (approximately proportional to ℓ^2 or $W^{2/3}$) and catabolism (outflow) proportional to body volume (proportional to W). Actually, catabolism is usually a power function of W with an exponent of about 0.8. According to Ursin (1967) and Beyer (1976), Equation (12) was first advanced by Pütter in 1922 and rediscovered by von Bertalanffy a decade later. The solution of Equation (12) is

$$W = W_\infty (1-e^{K(t-t_0)})^3 \tag{13}$$

where $K = H_2/3$, W_∞ $(H_1/H_2)^3$ and t_0 is the value of t when W=0. For ℓ proportional to the cube root of W, Equations (13) and (11) are equivalent.

Examples of the von Bertalanffy function and the data to which they were fit are given in Figure 4. The von Bertalanffy function usually describes the length or weight of fish at age reasonably well even though biotic and abiotic factors (food density and temperature, for example) are ignored. The quality of the fit to data indicated in Figure 4 is typical for exploited fish. In the examples, observed length is usually within 20 percent of the length predictions based on the functions. Variability is greater in terms of weight, but the mean weight or length of fish of a particular age is usually much less variable from year to year. Therefore, the mean rate of production per fish of a particular species and age group may not be a significant source of variability in the rate of production by exploited fish populations. This is particularly true in light of the substantial variability in recruitment (as discussed below).

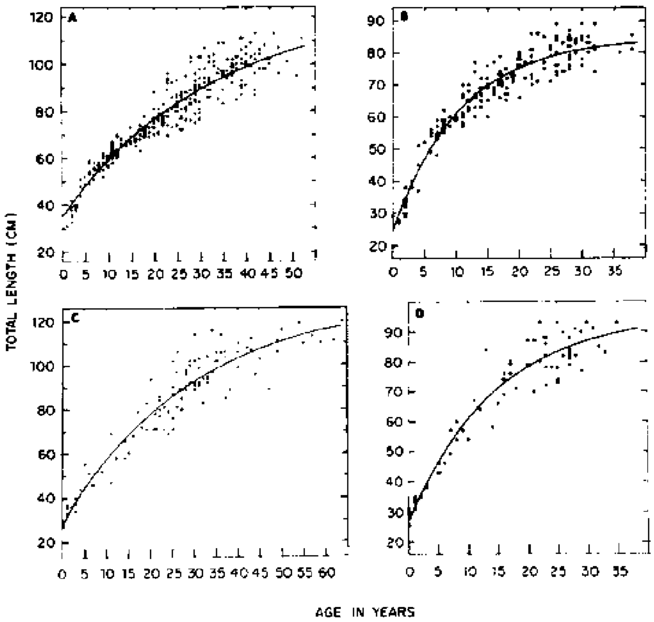

Figure 4. Examples of the von Bertalanffy function for dogfish *(Squalus acanthias)* and the data to which the functions were fit (Ketchen, 1975).

Another curve which can be used to describe growth in weight is the Gompertz function (Richards, 1959; Sillman, 1967):

$$W = W_0 e^{S(1-e^{-st})} \tag{14}$$

where W is weight at any age (time) t, measured from the time t = 0 when the fish would have had weight W_0; S is the instantaneous growth rate at t = 0; and s describes the rate of decrease in instantaneous growth rate. The Gompertz function

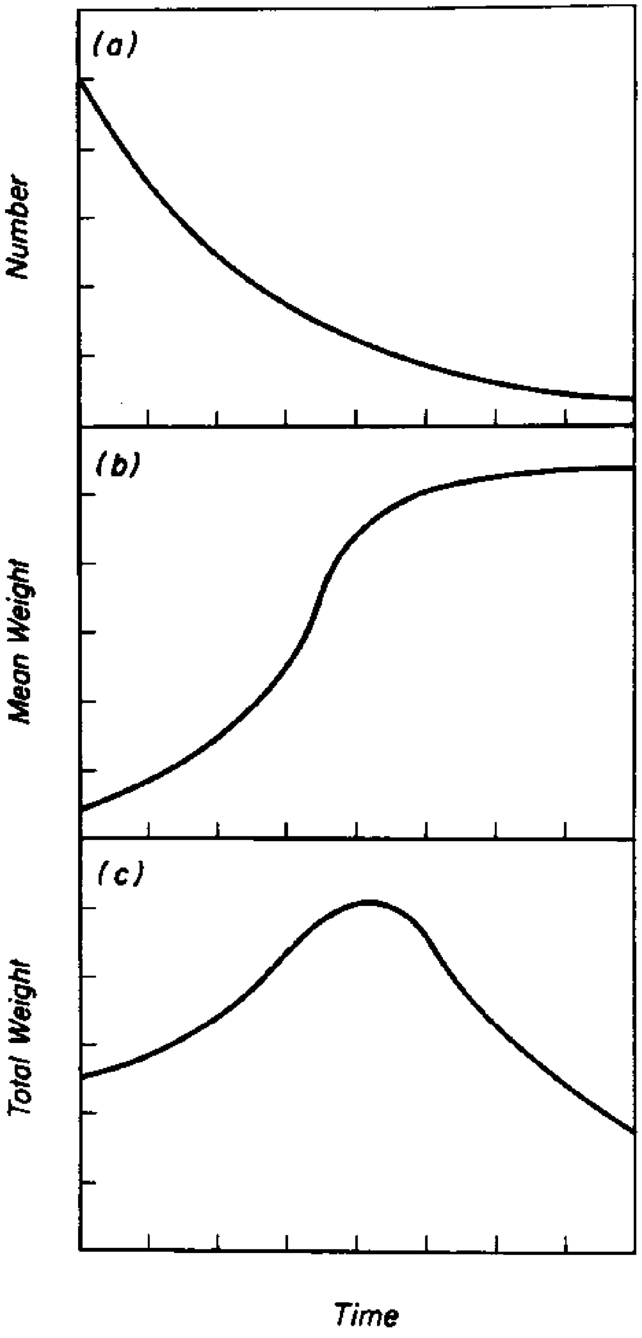

Figure 5. Time history of the number of fish (a), average weight of a fish (b), and the total biomass of a hypothetical cohort of fish (c).

is S-shaped with both a lower and upper asymptote; it has a point of inflection at a little more than a third of the distance between the lower and upper asymptotes.

The Gompertz model usually describes a weight/age relationship quite well, even for young fish. It, too, can be adapted for length data, with the model being that part of the curve above the inflection point.

Production by a Year Class

Net production by a given year class (cohort of fish spawned during the same year) is the difference between the sum of the weight gained by individuals in the population and the sum of the weight of fish loss due to death.

Figure 5 gives an example of the time history of the number of surviving individuals of a year class (N), the average weight of an individual of the year class ($\overline{w}$), and the total biomass of the year class ($N \cdot \overline{w}$). The maximum possible yield from a particular year class is the peak of the total biomass curve. To obtain this yield, the entire biomass must be harvested instantaneously, which is usually impossible and economically unacceptable. A central problem of fishery science has been to model yield for combination of fishing mortality rate (F) and age at which a year class is first exploited (t_c).

Baranov's Method

For fish stocks in which the average growth rate in length is constant for all fish which are of exploitable size, and weight is proportional to the cube of length, yield per recruit to the exploitable population (YPR) can be calculated by Baranov's (1918) method. The method also assumes that recruitment is spread uniformly through the recruiting year. Because of these assumptions, length can be used as a measure of time. For fishing mortality F, the yield per recruit in weight is as follows:

$$\mathrm{YPR} = v\, F\, L^3\, Q/Z \tag{15}$$

where v is the proportionality constant between W and L^3, Z is total mortality (M+F), L is the length at recruitment, and

$$Q = \frac{3}{LZ/d} + \frac{6}{(LZ/d)^2} + \frac{6}{(LZ/d)^3} \tag{16}$$

This form of the yield equation lends itself nicely to examination of changes in YPR induced by changes in F and L.

Although the method of Baranov is sound, its assumptions limit its usefulness. There are the following problems: (1) in most fish populations the average rate of increase in length is not constant for exploitable size fish; (2) for some species weight is not proportional to length cubed; (3) there are no factors in the formula to account for partial recruitment; and (4) there is no allowance for different mortality rates inflicted on different length groups of commercial size fish.

Ricker's Method

Ricker's (1945) method of calculating yield is flexible enough to overcome all the aforementioned problems of Baranov's method. Ricker partitioned the exploitable life span of a fish into time periods such that the mortality rate and the growth rate could be assumed constant during each time period. Briefly, if F_t is the instantaneous fishing mortality rate for time period t, and $\overline{B}_t$ is the mean biomass for the period t, then

$$\text{YPR} = \frac{1}{R} \sum_{t=t_c}^{t=t\lambda} F_t \overline{B_t} \tag{17}$$

where t refers to successive time periods (intervals), t_c being the first exploited period and $t\lambda$ the last period. The mean biomass at time t is calculated as

$$\overline{B_t} = \int_0^1 B_x \, dx \tag{18}$$

$$= \int_0^1 B_0 e^{(G_t - Z_t) x} \, dx \tag{19}$$

$$= \frac{B_0}{Z_t - G_t} (1 - e^{G_t - Z_t}) \tag{20}$$

where G_t and Z_t are the growth and death rates, respectively, during the period t, and B is the fish biomass at the beginning of the period.

Beverton and Holt's Method

The Beverton and Holt (1957) model for yield per recruit is similar to Baranov's method, except that the von Bertalanffy weight/age function, Equaion (13), is used in place of the assumption of a constant rate of growth in length. For R recruits at age t_r which are actually first exploited at age $t_c \geq t_r$, the yield rate for $t \geq t_c$ is

$$\frac{dY}{dt} = FB = FBW_\infty \cdot [(1 - e^{-K(t-t_o)})^3] \cdot [e^{-(t-t_c) Z}] \bullet [e^{-(t_c - t_r) M}] \tag{21}$$

Integrating from t_r to ∞ and dividing by R,

$$\text{YPR} = Fe^{-(t_c - t_r) M} W_\infty \sum_{i=0}^{3} \frac{J_i e^{-K(t_c - t_r)}}{Z + iK} \tag{22}$$

where $J_i = 1, -3, 3$, and -1 for $i = 1, 2, 3$, and 4, respectively. The Beverton and Holt yield per recruit model has been generalized to allow consideration of relationships between W and L other than cubic (Jones, 1957; Paulik and Gales, 1964) by expressing Equation (22) in a form that would allow the evaluation of YPR using tables of the incomplete beta function.

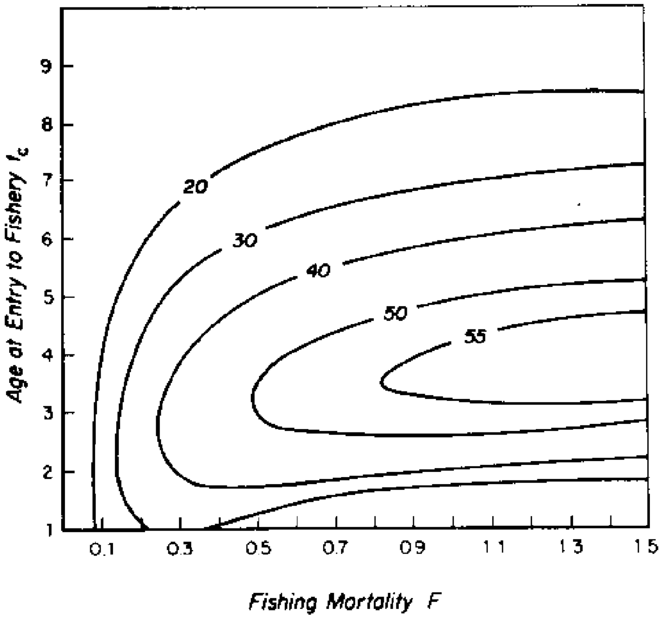

Figure 6. Yield per recruit isopleths for sea herring (Anthony, 1972) calculated by Beverton and Holt's method.

Equation (22) allows examination of the effect of t_c and F on YPR. An example of YPR isopleths for the Atlantic sea herring is given in Figure 6. For any particular value of t_c the fishing mortality rate that maximizes YPR is called F_{max}. Because of the unexplained variability in recruitment, it was common in years past for fishery scientists to recommend maximizing yield per recruit for each entering year class, ignoring the factors that control year-class strength. Unfortunately, a fishing mortality of F_{max} results in a substantial reduction in spawning stock size and may adversely affect future recruitment. Also, the marginal yield per unit of fishing mortality (and fishing effort) approaches zero as F approaches F_{max}. An alternative though arbitrary target fishing mortality rate is $F_{0.1}$, which is the fishing mortality rate at which the slope of the YPR function for a particular t_r is 10 percent of the slope of the function at $F = 0.0$. A fishing mortality of $F_{0.1}$ results in only a minor reduction in lifetime yield from a cohort of fish with a much smaller reduction in spawning stock size relative to F_{max}. $F_{0.1}$ is apparently superior to F_{max} on economic grounds (Gulland and Boerma, 1973). Clearly, the marginal YPR is higher at $F_{0.1}$ than at F_{max}. A hypo-

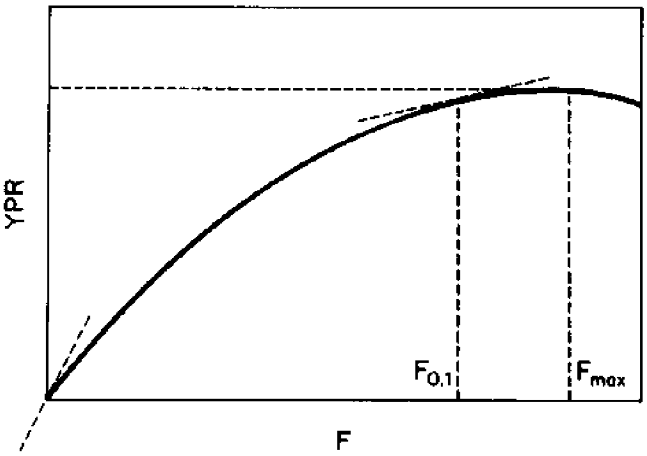

Figure 7. Hypothetical yield per recruit curve for a particular value of t_c. F_{max} and $F_{0.1}$ are also shown. Note that slope of curve at $F_{0.1}$ is 10 percent of slope through the origin.

thetical yield per recruit curve for a particular value of t_c is given in Figure 7. F_{max} and $F_{0.1}$ are indicated for the hypothetical curve.

Stock-Recruitment Models

As noted earlier, most of the variability in production by exploitable marine fish populations results from variability in recruitment. Cushing and Horwood (1977) noted that recruitment may vary by up to a factor of 100. Variability in recruitment is certainly related to abiotic factors (such as climatic conditions). While attempts to relate recruitment to the size of the spawning stock have not been particularly successful, such attempts have been made.

The two most commonly considered stock-recruitment (S-R) models are attributed to Beverton and Holt (1957) and Ricker (1958). Cushing (1971) also proposed an exponential relationship between stock and recruitment, as in Equation (2). Cushing's exponential model is similar in shape to the Beverton and Holt S-R model. Numerous other formulations are also possible (Larkin, Raleigh, and Wilimovsky, 1964, for example). Only the Ricker and Beverton and Holt models will be discussed further in this paper.

Ricker distinguished two types of mortality during the prerecruit stage of the life cycle: density-independent and density-dependent mortality. Ricker hypothesized that density-dependent mortality is caused by cannibalism and therefore the density-dependent mortality rate is proportional to the density of the spawning stock. The biological mechanism of cannibalism leads to

$$R = A\,S\,e^{-DS} \qquad (23)$$

where A is the coefficient of density-independent mortality and D is the coefficient of density-dependent mortality. For multi-age spawning species, S (the size of the spawning stock) and R are measured in eggs spawned and lifetime egg production of recruits suffering only natural mortality, respectively (Ricker, 1973c). Equation (23) can also be explained biologically if larval growth is density-dependent (as might occur when larvae compete for food) and mortality decreases when the larvae reach and exceed a critical size (Beverton and Holt, 1957).

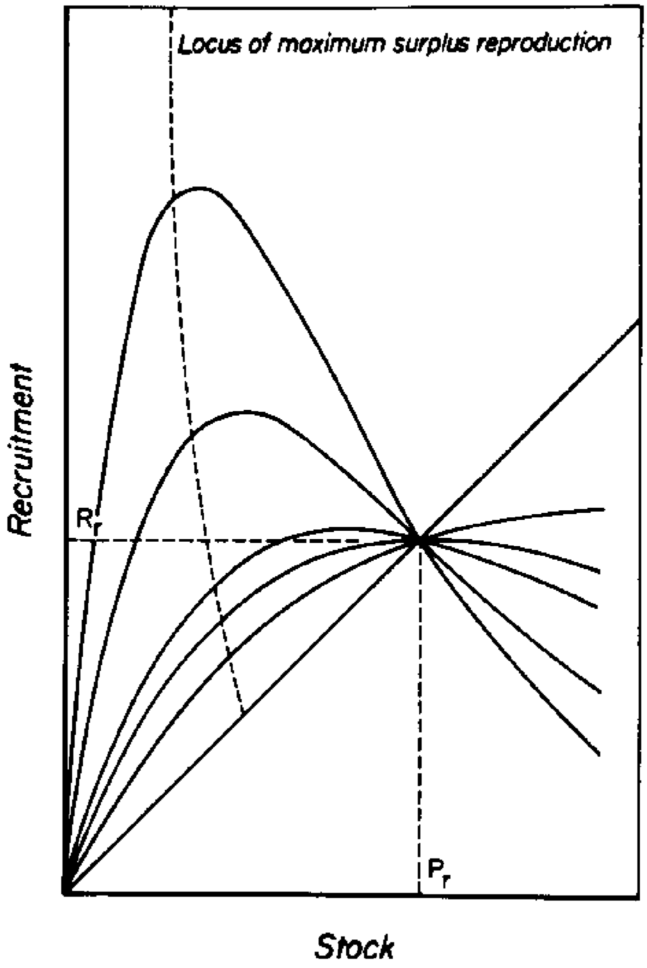

Figure 8. Family of Ricker stock-recruitment functions.

The family of Ricker curves is plotted in Figure 8. The straight line at a 45° angle to the horizontal axis is the equilibrium line. For points

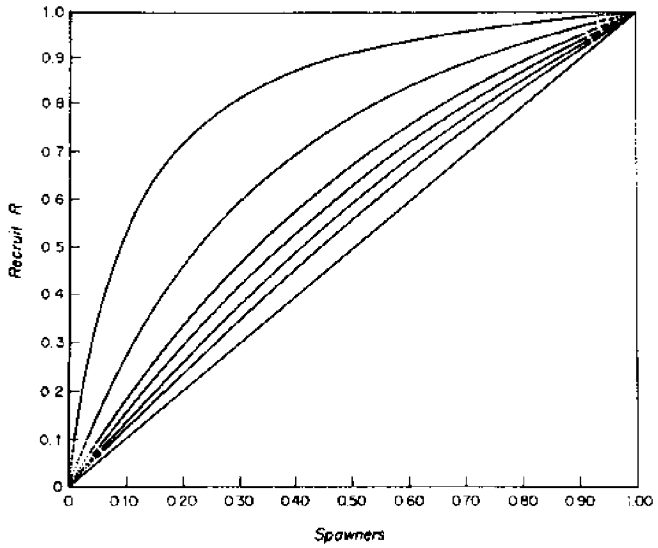

Figure 9. Family of Beverton and Holt stock-recruitment functions.

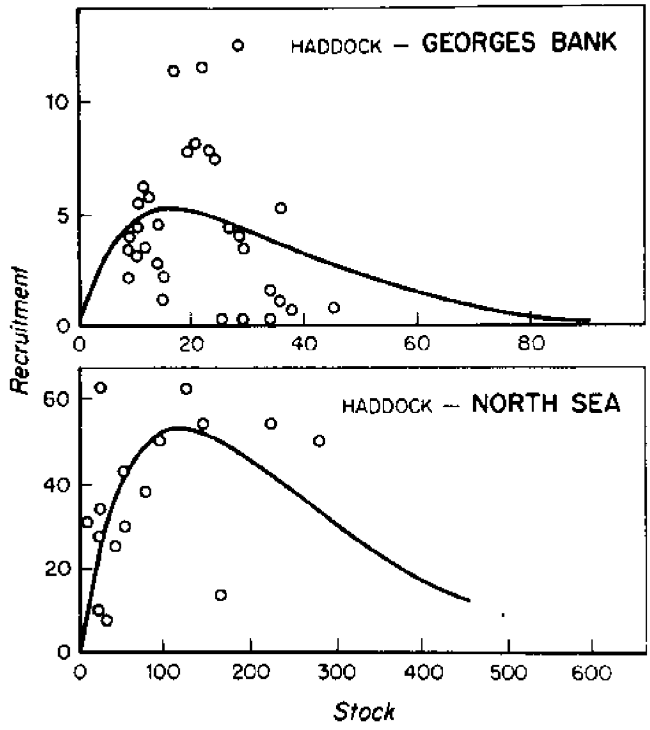

Figure 10. Ricker stock-recruitment function fit to data for two haddock stocks (Cushing, 1973).

above the 45° line, recruits more than replace their parents and the stock grows when there is no fishing. For points below the 45° line, the size of the population declines. The equilibrium yield expressed in recruit eggs is equal to the vertical distance between the curve and the 45° line for each value of S.

Beverton and Holt (1957) also considered both density-dependent and density-independent mortality, but they assumed that density-dependent mortality is linearly related to larval density during a limited time period. For A and D still representing the coefficient of density-dependent and density-independent mortality, respectively,

$$R = \frac{1}{A + D/S} \qquad (24)$$

A family of Beverton and Holt curves is plotted in Figure 9 with a 45° line. The equilibrium yield for each curve is again represented by the distance between the curve and the 45° line for a particular value of S. Ricker (1973) tabulated critical characteristics of Equations (23) and (24) such as: (1) size of the spawning stock needed to maximize recruitment, (2) maximum equilibrium exploitation rate, and (3) size of spawning stock needed to support the maximum equilibrium catch.

The Ricker S-R function has been more widely applied to fish populations than the Beverton and Holt function. Dome-shaped functions, such as Equation (23), are apparently more effective in fitting data for two weakly related variables regardless of the biological justification for the function. Also, because of confounding of the dependent and independent variables when Equation (23) is linearized, the fit of the Ricker model to a pair of randomly generated series of numbers often appears statistically significant. Thus, a nonlinear fitting procedure (such as in Marquardt, 1963) should be used when applying the Ricker S-R function.

A stock-recruitment function can be combined with a yield per recruit analysis. Beverton and Holt (1957) and Walters (1969) developed combined S-R and YPR models. These self-generating models (with respect to recruitment) can be used to simulate populations and examine sustainable yield. Unfortunately, these are deterministic models, and it is unrealistic to ignore the stochastic nature of the system. This point was clearly demonstrated for surplus production models (which are discussed below) by several recent papers.

Examples of the Ricker S-R function along with the data to which the functions were fit are given in Figure 10. Substantial unexplained variability remains, but this situation is not unusual. In fact, the traditional stock-recruitment functions probably fail to explain a statistically significant portion of the observed variability in recruitment for most fish populations. This failure may partially result from the inadequate data bases (both quantity and quality) available to describe stock and recruitment.

Because of the observed variability in recruitment, some authors (Thompson and Bell, 1934; Graham, 1935) have concluded that recruitment is independent of spawning stock size. Actually, the underlying relationship between recruitment and spawning stock size may be obscured by environmentally related noise, but an S-R relationship must exist, particularly at low levels of spawning stock size. Recruitment of the Georges Bank haddock stock is quite variable and an S-R relationship has not been resolved empirically, but recruitment has been generally lower and more variable when the spawning stock size is small (Grosslein and Hennemuth, 1973). During the period from 1964 to 1977, only the 1975 year class was exceptionally strong and all others were below average size. During this same period the spawning stock size was extremely low as a result of overfishing. From 1935 to 1960, when spawning stock size was much higher, year classes as large as the 1975 year class occurred about every third year. Thus, environmental conditions may have to be particularly favorable when spawning stock size is low for a strong year class to be produced.

In some cases, variability in recruitment unexplained by an S-R function can be explained by anomalies in abiotic conditions. For Atlantic menhaden, Nelson, Ingham, and Schaaf (1977) correlated deviations in recruitment from a Ricker S-R function with anomalies in zonal Ekman transport. The authors' hypothesis is that strong inshore transport increases the probability of eggs and larvae reaching inshore nursery grounds and thus enhances year-class strength. Sissenwine (1974, 1977b) found that correlations between temperature and recruitment for southern New England yellowtail flounder were so strong that no relationship between spawning stock size and recruitment could be detected. Considerable care is necessary when interpreting correlations between biological phenomena (such as recruitment) and measures of climatic conditions when the mechanism responsible for the correlation is unknown. It is advisable to test such correlations on a second independent set of data. This points out the need for long-time series of biotic and abiotic data.

Cushing (1973) noted that recruitment of some stocks is more stable in the face of climatic changes than others. For example, recruitment of the Arcto-Norwegian cod stock fluctuates only moderately, whereas recruitment of the Norwegian herring stock fluctuates drastically. Cushing (1971 and 1973) makes the following generalizations:

(1) Recruitment is more variable at the edge of the range of species.

(2) Recruitment is more variable for a population comprised of fewer year classes. The number of year classes in a population is decreased by fishing.

(3) The degree of density dependence between spawning stock size and recruitment is inversely related to fecundity. Density dependence tends to stabilize populations.

There are probably numerous exceptions to these generalizations. The increased variability in recruitment as the number of year classes in a population decreases (number 2 above) may reflect spawning stock size.

Surplus Production Models

There is often inadequate information available to distinguish between components of production of a fish population resulting from growth and recruitment. Therefore, surplus production (SP) is sometimes related to stock biomass (B) empirically and the empirical relationship is used to model the effect of fishing on the population.

Models relating surplus yield to biomass usually assume that SP is greatest at an intermediate level of B, not at maximum population biomass, B_{max}. Ricker (1975) notes three reasons for a smaller surplus production at higher stock densities: (1) near maximum stock density, efficiency of reproduction is reduced, and often the number of recruits is less than at smaller densities; (2) if food supply is limited, food is less efficiently converted to fish flesh by a large stock than by a smaller one; (3) an unfished stock tends to have more older fish, relatively, than a fished stock. This results in decreased production because: (a) larger fish tend to eat larger foods, so an extra step may be inserted in the food web, with a consequential loss of efficiency of utilization of basic food production, and (b) older fish convert a smaller fraction of the food they eat into new flesh, partly because they utilize a lot of their food for producing eggs and milt.

Under stable environmental conditions, recruitment and growth are balanced by natural mortality for an unexploited population; thus, there is no surplus production. When fishing begins, biomass is reduced and the available food is used more efficiently by the remaining population. Thus, surplus production is generated so that the population would recover to B_{max} if fishing were stopped. Ricker (1975) attributes these hypotheses concerning the relationship between production and population biomass to Peterson (1922) and Baranov (1926 and 1927).

Graham (1935) incorporated these ideas into a model of surplus production. He assumed that the instantaneous rate of surplus production per unit of biomass $(\frac{1}{B}\frac{dB}{dt})$ is directly proportional to the difference between the actual biomass and the carrying capacity the area will support. The specific model is

$$\frac{1}{B}\frac{dB}{dt} = r\,(B_{max} - B) \tag{25}$$

where r = instantaneous rate of increase of stock at a density approaching zero.

Application of Equation (25) to fisheries was popularized by Schaefer (1954, 1957). Schaefer applied the model to time series of annual fishing effort (f) and annual average catch per unit of fishing effort ($\bar{U}$) for Pacific halibut and yellowfin tuna where f is proportional to F and $\bar{U}$ is proportional to $\bar{B}$. An additional term, qf, where q is the catchability coefficient (such that F=qf), was included in Equation (25) to account for exploitation. When q has been estimated independently, equilibrium catch (CE=SP) for each year i is estimated by $(\bar{U}_{i+1} - \bar{U}_{i-1})/2q + \bar{U}_i f_i$. The two parameters of the model are then estimated by fitting a relationship between estimates of CE and $\bar{U}/q$. Pella and Tomlinson (1969) give evidence that Schaefer's method of estimating CE is inadequate. Where q is unknown, CE can be estimated along with the other two parameters of the model by partitioning the series of observations into contrasting sums, and, together with the total sum, a system of three equations and three unknowns is established and solved.

The model parameters are more easily estimated by simple linear regressions under the assumption of equilibrium. This approach was outlined by Gulland (1961) and further explained by Gulland (1969).

For the Schaefer model, as Equation (25) is now widely known, the maximum equilibrium catch or maximum sustainable yield (MSY), fishing mortality rate that produces MSY (F_{msy}) and the biomass that produces MSY (B_{msy}) are

$$MSY = \frac{r\,B^2_{max}}{4} \tag{26}$$

$$F_{msy} = \frac{r\,B_{max}}{2} \tag{27}$$

$$B_{msy} = \frac{B_{max}}{2} \tag{28}$$

Pella and Tomlinson (1969) argue that the functional relationship between dB/dt and B is not always symmetric, as with Equation (25), and therefore they considered a more general model where the surplus production rate equals a linear combination of B and B^m for any value of m. A family of generalized surplus production curves is plotted in Figure 11. The quadratic function, m=2, Equation (25), is still most widely used because it is more easily fit to data (particularly under the assumption of equilibrium). Furthermore, the available data to which surplus production models are fit are often inadequate to indicate the degree of asymmetry in the functional relationship between dB/dt and B.

As noted by Gulland (1961), the relationship between U and f is linear for Equation (25) when at equilibrium. Ricker (1975) describes possible biological reasons for a curvilinear relationship. Fox (1970) proposed a Gompertz function as a model relating surplus production to population size which results in a functional relationship between surplus production and fishing effort of the same form as the Ricker stock-recruitment function, Equation (23), and an exponential relationship between U and f at equilibrium. Pella and Tomlinson's (1969) generalized surplus yield model approaches Fox's (1970) exponential model as m approaches 1. An example of the exponential model is also given in Figure 11. The biomass that produces MSY is about 37 percent (e^{-1}) of B_{max}.

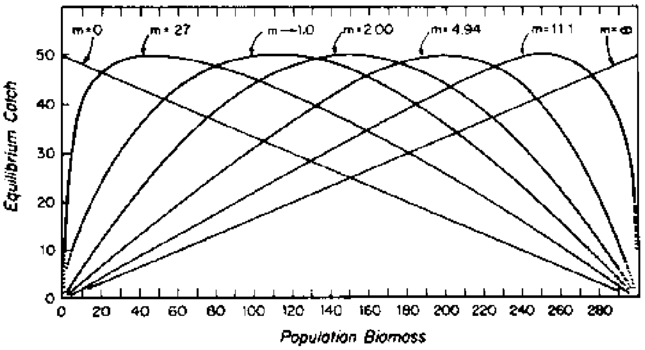

Figure 11. Family of Pella and Tomlinson (1969) generalized surplus yield equations and an example of Fox's (1970) exponential model (M → 1).

Two glaring deficiencies limit the usefulness of the preceding models: (1) there is no time lag between the change in population size and the change in the rate of population increase, and (2) the rate of population increase is assumed independent of the age composition of the population. Walter (1973) proposed two surplus production models (to be fit to catch and effort data) to account for time lags. The models assume that density-dependent growth and mortality are proportional to the biomass at some previous time. Marchesseault, Saila, and Palm (1976) also proposed a surplus production model incorporating a time lag.

Recently Walter (1978) proposed a model which offered a modification of the basic Schaefer formation by taking into account changes in recruitment. Recruitment is treated as an impulse (added to B) once a year, and the dynamics of population biomass are described by Equation (25) between impulses of recruitment. Walter provided expressions for long-term equilibrium yield under assumptions of a linear and density-dependent stock-recruitment relationship.

Other variations of the Schaefer model have been considered in recent years. Schnute (1977) allowed for stochastic variation in the fishery and provided a method for predicting yield in future years. Pope (1975a and 1975b) modified the Schaefer model in order to determine optimum yield in a mixed fisheries situation by attempting to account for biological interactions between species. Pope concluded that interactions cause the combined MSY to be less than the sum of the individual MSYs of the species. Brown et al. (1976) came to the same conclusion when applying the Schaefer model to total catch (all species combined) per effort and total fishing effort for the fisheries of the U.S. continental shelf north of Cape Hatteras.

The surplus production models described above ignore the year-to-year effect of environmental fluctuations on populations. They also ignore (with a few exceptions) the direct effect of species interactions. Thus, considerable unexplained variation in surplus production is likely. Fishery scientists often assume that when a surplus production model is fit to a time series of data that extends over periods of both favorable and unfavorable environmental conditions, the model will provide a useful representation of the stock production relationship for average conditions. Furthermore, it is often assumed that management based on the model will produce the predicted results on the average. For example, it is often assumed that a fishing mortality of F_{msy} will produce a long-term average yield of MSY from a population fluctuating about an average size of B_{msy}. Doubleday (1976) and Sissenwine (1977c) demonstrated that in fact, for a fluctuating environment, the long-term average yield and population size will probably be lower than predicted by the Schaefer model. Beddington and May (1977) conclude that as F increases toward F_{msy}, variability in population biomass increases. Thus, it is unrealistic to ignore environmental fluctuations when applying deterministic surplus production models.

Ecosystem Models

Most of the models already described in this paper ignore the interaction of exploited populations with their biotic and abiotic environment. Fishery scientists are aware of the inadequacies of these research tools and temper their use accordingly (see Assessment by Projection based on Current Stock Status).

There are several current attempts at modeling exploited ecosystems. The Northwest Marine Fisheries Center (NMFS) has implemented a "Dynamical Numerical Marine Ecosystem Model" (DYNUMES, Laevastu and Favorite, 1976). Biotic and abiotic processes are integrated in DYNUMES. The model is essentially time-dependent and two-dimensional, with the third dimension (depth distribution of some species, temperature, currents, etc.) implicit in some parts. The model is currently applied to the eastern Bering Sea, which is represented by equal area boxes. The biological information is based on a mass balance equation similar to Equation (1). At present, primary production and nutrient cycling are ignored in the model and secondary production is input to the model exogenously. The model permits simulation of the dynamics of abundance and distribution of each species group as affected by species interactions such as predation, environmental factors such as temperature and currents, and man's activities such as fishing. Currently, the model does not treat the mechanisms which control survival of early life stages adequately to allow prediction of recruitment.

Another major ecosystem modeling effort has been described in numerous unpublished reports submitted to the International Council for Exploration of the Sea (ICES) by E. Ursin, K. P. Andersen, and H. Lassen of Denmark (Andersen and Ursin, 1977a and 1977b). Their model of the North Sea assumes horizontal homogeneity, with the water column divided vertically into a euphotic and deep water layer. Primary production and nutrient cycling are modeled. The animal compartments are modeled using the Beverton and Holt yield per recruit approach with modified formulations of growth and natural mortality. Growth is based on consumption rate, which depends on the availability of suitable size food. The model assumes only a size preference for food (no species preference). Natural mortality of each species reflects the total internal consumption of that species. Recruitment is not modeled internally. A recruitment parameter for each species is allowed to vary annually to conform to observed events (Andersen and Ursin, 1977b, page 400).

The Northeast Marine Fisheries Center (NMFS) is now conducting extensive biological and physical oceanographic surveys which will eventually be used to formulate models of components of the Northwest Atlantic ecosystem. Biological surveys monitor abundance, species composition, and age composition of plankton, benthos, and nekton. Predator-prey interrelationships are being quantified based on the examination of the stomach contents of thousands of fish (more than 70,000 to date). Special laboratory studies on the physiology of larval fish are also underway. Vertical temperature profiles are determined at most biological sampling stations and occasionally current meters are deployed. A preliminary energy flow model of Georges Bank has already been developed. A major field program which may elucidate some of the biotic and abiotic factors that determine year-class strength will be implemented in 1978. Several oceanographic research vessels will simultaneously and continuously monitor a patch of herring larvae and as many potentially related factors as possible. Shipboard laboratory studies will also be conducted in conjunction with the field program. Even this extensive program is inadequate to provide all the information required to develop a realistic ecosystem model.

The ecosystem modeling approach is a tool for gaining general insight into marine biological processes, but verified models with proven predictive ability are not yet available. Beyer (1976) points out several biological problems which must be addressed before predictive models with a time horizon of longer than a few years are possible for the North Sea, one of the world's most intensively studied regions. These are as follows: Why does year-class strength fluctuate irregularly? What competitive mechanisms exist between species in larval and juvenile stages? What kind of opportunistic species move in and eat the fish left alone after their predators have been fished down? Currently, predictive ecosystem models with a time horizon of even a few years do not exist.

Assessment by Projection Based on Current Stock Status

In the jargon of agencies responsible for fishery management, the term stock assessment means the application of fishery science to a stock of fish in order to evaluate or assess its current condition and predict its future condition relative to specific resource management decisions. Stock assessments have played an increasing role in management decisions of such international organizations as the Northeast Atlantic Fisheries Commission (NEAFC), the International Commission for the Northwest Atlantic Fisheries (ICNAF), International Tropical Tuna Commission (ITTAC), the International Commission for Conservation of Atlantic Tuna (ICCAT), the International Pacific Halibut Commission (IPHC), and the International North Pacific Fisheries Commission (INPFC). Now with extension of coastal state jurisdiction, management agencies of several individual countries (such as Canada, Iceland, and the United States) are even more dependent on stock assessments. Earlier fisheries management relied primarily on regulations applicable to equilibrium conditions. These involved fishing net mesh size regulations, minimum size limits, spawning or prespawning area closures, and, in some cases, such as the Pacific halibut (Skud, 1973), regulation designed to limit catches based on estimates of maximum sustainable yield. However, in the 1970s, as fishing effort began to increase for almost all species and declines in production were noted for numerous stocks, concern began to be expressed as to the effectiveness of these regulations. Thus, noting the variability in fish production, attempts have been made to manage stocks by regulating yearly catch and fishing mortality.

This section will outline some assessment procedures in common use. The next section will discuss their current application to fisheries off the northeastern United States.

Before one can evaluate current stock conditions, previous levels of abundance have to be estimated. Baranov's (1918) catch equation is used to estimate past stock size. The catch equation is the solution of a differential equation similar to Equation (21), expressing catch rate in number of fish instead of weight. The equation is

$$C_{ij} = \frac{N_{ij} F_{ij}}{Z_{ij}} (1 - e^{-Z_{ij}}) \qquad (29)$$

where i = year

j = year class

C_{ij} = catch in numbers in year i for year class or cohort j

N_{ij} = size in numbers at the beginning of year i of year class j

F_{ij} = fishing mortality

M_{ij} = natural mortality

Z_{ij} = total mortality = $M_{ij} + F_{ij}$.

If C_{ij}, F_{ij}, and M_{ij} (and therefore Z_{ij}) are known, then Equation (29) can be solved for N_{ij} numerically.

A second equation is applied in conjunction with Equation (29):

$$N_{i+1,j} = N_{i,j} e^{-Z_{ij}} \qquad (30)$$

By manipulating Equations (29) and (30) together, N_{ij} and F_{ij} can be calculated for all past years of life of the cohort if the entire catch history of the cohort and natural mortality are known and the fishing mortality in the last year that the cohort is fished (terminal F) is estimated or assumed. This procedure is called virtual population analysis (VPA) or cohort analysis. The mechanics of sequential computations with the catch equation were described by Ricker (1948). The method was popularized by Murphy (1965) and Gulland (1965). Solution of an approximate form of the catch equation was also called cohort analysis by Pope (1972). When the analysis is applied several years into the past, the results are insensitive to the estimated or assumed value of terminal F (Jones, 1961).

These same two equations are also used to project into the future. If the current N_{ij} is known along with M_{ij} and F_{ij}, then $N_{i+i,j}$ can be calculated for any particular C_i in the upcoming year. Unfortunately, errors in the current estimate of N_{ij} are propagated when projecting into the future. Therefore, projections are usually limited to a few years. In order to make projections for an entire population, the N_{ij}s are summed over all year classes. Recruitment is accounted for by adding the recruiting cohort each year and projecting this along with all of the others. Possible catches in year i can be predicted for given target fishing mortality rates such as F_{msy} and $F_{0.1}$, and the resulting stock size evaluated.

The resulting tabulation of various F_{ij} and $N_{i+i,j}$ and the sum of the $N_{i+1,j}$ for all cohorts provides the bases for management decisions. Furthermore, knowledge of the resulting stock by age and size allows the evaluation of changes in spawning stock size or potential egg production. Stock size and catch can also be expressed in weight by multiplying N_{ij} by the appropriate mean weight of individuals of the cohort or by substituting $G_{ij} + Z_{ij}$ for Z_{ij} in Equation (29), where G_{ij} is the instantaneous growth rate and C_{ij} and N_{ij} are expressed in weight.

While the above is conceptually quite simple, in application it can be a very involved task. In order to utilize this procedure, one first needs to know the catch in numbers at age, which can be difficult to obtain. Numbers in the catch by age are usually estimated from samples of the catch. Age is determined by examination of hard parts of fish, usually their otoliths or scales. Some error is associated with the aging process, but the actual amount of error is usually unknown. Since the age of a fish is much more difficult to determine than its length, usually only a subsample of the fish measured is actually aged. An age/length key is developed for prorating the estimated length composition of the catch into ages. Natural mortality (M) must also be estimated, and in many fisheries this is the most difficult task. Therefore, several estimates are often used to evaluate the sensitivity of the results to estimates of M. There is sometimes a concern that a portion of the catch may not be known (e.g., discard or unreported recreational catch). If this does occur, then estimates and projections of the absolute size of the population will be inaccurate, but estimates of relative population size are valid where the proportion of unreported catch is constant.

Equations (29) and (30) are useful for estimating the past history of the fishery (as recent as perhaps 3 to 5 increments of i ago depending on the fishing mortality rate) given catch at age data. For projecting into the future it is necessary to have an estimate of current fishing mortality or stock size and to predict recruitment from some independent source. Resource surveys are one source of independent information. For example, virtual population analysis can be used to estimate recruitment during a series of previous years. A functional relationship is then fit statistically between estimates of recruitment and survey catch rate of prerecruit fish. Then, using this relationship and the current survey catch rate of prerecruits, recruitment in the upcoming year can be estimated. Unfortunately, an adequate time series of research vessel survey data is available for only a small portion of exploited marine fish populations.

Occasionally, other sources of independent information are available to estimate recruitment such as a juvenile fishery, as is the case with Atlantic sea herring. Obviously, models relating recruitment to abiotic factors may provide useful information for population projections. Where recruitment estimates are not available, the catch equation can still be used to project the status of the stock by assuming a value for recruitment based on the frequency distribution of observed past recruitment. For example, one can assume a recruitment level that is the lowest ever observed, a level exceeded 25 percent of the time, one exceeded 50 percent of the time, etc. Monte Carlo simulation can be used to determine the distribution function of projected stock size for a particular future catch rate. The managers then have to decide what level of risk they wish to take.

The fishing mortality rates F_{ij}s for the current year also have to be estimated from independent sources. The usual procedure is to divide a measure of relative abundance of the fully recruited fish (such as commercial or survey catch rate) into the total catch to obtain a measure of fishing effort (for commercial data) or relative exploitation rate (for survey data) and to functionally relate these to fishing mortality. The function is fit statistically to past estimates of fishing effort or relative exploitation rate and fishing mortality rate (calculated by VPA).

It is important to note here the inherent age specificity of F in these models. In reality, F is usually size specific, especially where size selective gear is used, and thus F_{ij} for age j is a function of the size at age j.

Often F_{ij} is nearly constant for a particular year i where j is greater than or equal the age (actually, size) at which the fishing gear has maximum catch efficiency. For the particular version of the Beverton and Holt YPR model described earlier, this age would be t_c; and all younger fish are assumed not to suffer fishing mortality. This situation is usually described as "knife edge" recruitment. In fact, there is usually a gradual transition from the prerecruit to the fully recruited stage. The ratio of the fishing mortality at age j to the fishing mortality of fully recruited fish indicates the degree to which age j is partially recruited. This ratio is called the partial-recruitment coefficient of age j. For some fisheries, fishing mortality declines for older fish. Here, the selection pattern of the fishery is represented by the ratio of F for each age j to the fully recruited F.

There is often considerable difficulty in estimating F_{ij} for recruiting year classes, as partial recruitment coefficients can differ considerably from year to year. For example, a very strong recruiting year class may attract additional fishing effort when the older year classes are not abundant. In such cases, survey cruise data may be used to estimate year-class size in the beginning of year i and then F_{ij} calculated directly from Equation (29). When historic catch at age data are not available, it may be possible to estimate the stock size at year i from areal expansion of survey cruise data or by calculating spawning stock size from estimated egg production based on egg surveys. Note that spawning stock size need not correspond to exploitable biomass. Current stock size can also be estimated from an empirical relationship of survey or commercial catch rate with previous independent estimates of stock size.

Projected stock size is usually compared to past stock size. An estimate of the percent change in stock size is sometimes calculated for each level of catch considered by managers. Sometimes the projected stock size is compared to a previously established minimum stock size constraint. The minimum stock size might be the smallest size that has parented strong year classes in the past. In other cases, an optimum stock size is chosen in order to stabilize the fishery and to increase availability of fish to particular user groups.

Research survey cruise catch rate trends can be related to commercial catch rate through appropriate modification of the catch equation even when the actual stock size is unknown. Since the ratio of commercial catch to survey catch rate should be proportional to fishing mortality rate, from the most recent survey catch rate one can estimate the catch that will correspond to the fishing mortality rate that occurred in any previous year. By taking past trends into consideration, one can make a reasonable judgment as to the direction of stock size change that would occur for given catches. Furthermore, if an estimate of F is available for any period in the past, F may be estimated for each of the other years. This is accomplished by substituting the survey catch rate times a constant into Equation (29) and solving for the constant where the equation is applied to the period of unknown F. Once the constant has been estimated, Equation (29) can be used to estimate F in other years for particular values of commercial catch and survey catch rate. This procedure is not sensitive to changes in partial-recruitment coefficients. Obviously, if these calculations have to be done in terms of weight rather than numbers, the procedure is subject to error to the extent the mean size in the fishery fluctuates.

Sometimes survey cruise data are more thoroughly analyzed. The following two models have been proposed as projection tools where survey catch rate has not been calibrated to actual population size. The first and simpler model is

$$\Delta U_i = a - bY_i + cR_i + \tilde{e}_i \qquad (31)$$

where ΔU_i is the change in survey catch (weight) rate during year i, Y_i is the total catch in weight, R_i is the survey prerecruit catch rate, and $\tilde{e}$ is an error term with mean 0. Thus, according to Equation (31) the size of a population would have a greater tendency to decrease the higher the annual catch and it would have a greater tendency to increase the greater the expected recruitment. The coefficients of the equation are fit by the least squares method. The second model provides a more rigorous description of population dynamics:

$$\frac{\Delta U_i}{U_i} = a - b\frac{Y_i}{U_i} + c\frac{R_i}{U_i} + \tilde{e}_i \qquad (32)$$

Here U_i is the survey catch (weight) rate corresponding to the beginning of the year during which a catch of Y_i is taken. For example, an autumn 1977 survey is assumed to correspond to the population size at the beginning of 1978. This equation is an approximation of an equation in which the instantaneous rate of change in population biomass is: (1) either directly or inversely proportional to current biomass, (2) proportional to the instantaneous recruitment rate, and (3) inversely proportional to the instantaneous catch rate.

Finally, predictions of catch can be made from surplus yield models with adjustments for disequilibrium, utilizing the procedure developed by Walter (1976). This procedure can be used to calculate the yield in a particular year corresponding to a given fishing mortality for a population which has an underlying Schaefer (1954) yield curve. The procedure could undoubtedly be extended to other surplus yield curves in the general production model family. This adjustment for disequilibrium does not account for variability in recruitment. Walter's (1978) surplus yield model, which accounts for variable recruitment using an impulse function, may also be applied. This model may prove useful for evaluation of fisheries where the parameters of a yield curve can be estimated and a yearly estimate of recruitment is available. It is too early to predict the extent to which this will be used on a yearly basis. Frequently, if an estimate of recruitment can be obtained, other age composition data are also available (the estimate of recruitment often will come from relating survey indices to results of cohort analyses). Therefore, it may be possible to apply the projection method based on the catch equation in many cases where Walter's (1978) method is applicable. Where both methods are applicable, their relative merit should be examined on a case-by-case basis.

None of the above procedures explicitly include species interactions and environmental effects. Since the current stock condition reflects the past history of the stocks, these effects are included in the evaluation of the current stock status implicitly. For short-term predictions these other factors may have little effect. For longer range prediction, the ability to include these factors explicitly could improve the assessments to the extent that data can demonstrate the validity of any relationship used. Environmental data may also be useful as an additional variable in stock-recruitment relationship studies, which are needed to clarify the determination of minimum and optimum stock sizes. Presently, for longer term simulation the best approach is to use recruitment generated from a probability distribution based on past observation. When populations of several species are simulated simultaneously, realistic results are obtained by using recruitment generated from a joint probability distribution function for all species. If the available data base is inadequate to estimate the joint probability distribution, the sum of production resulting from recruitment of all species should be bounded within the historically observed range.

Application to Fisheries off the Northeastern United States

One product of all the above models is a set of assessments available to managers to enable them to establish a fishery management regime based on their determination of optimum yield. Remember that according to the Fishery Conservation and Management Act of 1976, the determination of optimum yield requires the consideration of ecological, social, and economic factors. Although fishery management initially concentrated on a few key species, the continuous broadening of the scope of world fisheries and the greater understanding of the principles of ecological interrelationships have tended to drive fishery management toward a comprehensive approach. The most intensive application to date of fisheries assessment models in developing an ecosystem approach to management occurred in the waters off the coast of the northeastern United States in the year just prior to extension of fishery jurisdiction to 200 miles. In the northwest Atlantic north of the United States and the northeast Atlantic, similar, but less comprehensive, efforts have been made. In the territorial waters of Iceland an extremely detailed real time management procedure is being utilized and refined. The following discussion will be devoted to the area off the northeastern United States.

The two basic sets of data are utilized as input into fishery assessments in this area. The first is the catch data collected by the Branch of Statistics of the Northeast Regional Office of Fisheries of the National Oceanographic and Atmospheric Administration (NOAA). Samples taken by NOAA port agents are used by the Northeast Fisheries Center (NEFC) of NOAA to estimate age and length compositions. The recent data files exist at NEFC, and historical data have been published in Fishery Statistics of the United States (U.S. Government Printing Office) in yearly volumes. Catches not entering the commercial channels are not in these files, but estimates from angler surveys are published for 1960 (Clark, 1962), 1965 (Deuel and Clark, 1968), and 1970 (Deuel, 1973), and are available for 1974 in the files of the Branch of Statistics, NOAA, Washington, D.C. Foreign catch biostatistics are recorded in ICNAF Bulletins and are now submitted directly to the United States (since the implementation of extended jurisdiction). The second basic set of data used in assessments is from research vessel surveys. An extensive series of research survey cruise data (beginning in 1963) is located at the Northeast Fisheries Center.

Table 1 presents a list of the number of fish aged by NEFC in 1977, indicating the volume of such results being produced annually. This activity is necessary in conjunction with research surveys and the collection of commercial catch data. Fishery assessment requires a major commitment to monitor stocks on an ongoing basis.

Under ICNAF assessments were required for the following stocks (and it is likely they will be required in the future with extended jurisdiction):

cod—Gulf of Maine*
cod—Georges Bank-Middle Atlantic*
haddock—Georges Bank-Gulf of Maine*
pollock—Nova Scotia-Gulf of Maine-Georges Bank
redfish—Gulf of Maine
silver hake—Gulf of Maine
silver hake—Georges Bank
silver hake—southern New England-Middle Atlantic
red hake—Georges Bank
red hake—southern New England
yellowtail flounder—Georges Bank*
yellowtail flounder—southern New England*
other flounders—these were assessed as a group, but a start was made toward a separate evaluation for fluke
mackerel—Newfoundland to Cape Hatteras
sea herring—Gulf of Maine
sea herring—Georges Bank-Middle Atlantic
sea herring—Nova Scotia (basic analyses done by Canada, but all three stocks need to be considered simultaneously in developing assessments and management because of stock interactions)
Loligo squid—Georges Bank-Middle Atlantic
Illex squid—Georges Bank-Gulf of Maine-Middle Atlantic, considered in a complex with *Illex* squid off Nova Scotia and Newfoundland
other finfish—these were assessed as a group, with separate evaluations for butterfish and river herring, bluefish and alewife
total finfish plus squid—excluding menhaden and large pelagics.

Other species that have now been placed under management are surf clams, ocean quahogs, and northern shrimp.

The basic procedure utilized in each yearly

**Managed during 1977 under authority of Fishery Conservation and Management Act of 1976.*

assessment is to review all the current knowledge about the biology of the stock, all available data both quantitative and qualitative relative to the present status, and to try and relate this information on the stock situation to predict the relative effects of potential catches. This is best done in an interactive peer review situation, as is done in the Assessment Committee of ICNAF or in ICES Working Groups, where there exists a body of experienced assessment scientists. In contrast, the studies which give the scientific basis for estimation of model parameters that are used in the assessments are the works deserving of publication in the scientific literature.

The models discussed in the earlier section of the paper can now be reviewed in terms of their application to assessing the fisheries mentioned above. Table 2 describes the current status of assessments of the aforementioned stocks. It is clear from this table that fishery management of the region is based on a substantial body of information, but much still remains unknown.

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Table 1. Fish age determinations during 1977.

Species	*Number*
Redfish	2,032
Yellowtail	9,587
Mackerel	1,089
Cod	1,824
Haddock	4,183
Scallops	1,600
Pollock	649
Goosefish	30
Scup	200
Fluke	2,148
Silver Hake	3,982
Blackback	916
Sea herring	7,728
Alewives	1,000
Red hake	8,901
Total	45,869

Table 2. Current application of fishery assessments models to fisheries off the Northeastern Coast of the United States.

Stock	*Yield per recruit*	*Equilibrium surplus production models*	*Virtual population analyses (VPA)*	*Stock-recruitment model considerations*	*Projections based on catch equation*	*Evaluation of relative stock abundance*
Cod Gulf of Maine	Beverton and Holt yield per recruit model used to choose range of Fs considered in assessment. Also evaluation of effects of size at entry	Evaluated from historic catch statistics. No quantitative model	None	None	None	F from earlier analyses related to survey cruise trends and catch; catches by market categories are reviewed over time for changes in size distributions
Cod Georges Bank Middle Atlantic	Beverton and Holt yield per recruit model used to choose range of Fs considered in assessment. Also evaluation of effects of size at entry	Evaluated from historic catch statistics. No quantitative model. Several generalized production models fit, but none are considered viable in view of historical catches	First approximation available—but sensitivity to potential errors in age composition of catch unknown	No model, but historic stock sizes from VPA qualitatively used for evaluating minimum stock sizes appropriate from stock-recruitment standpoint	Done using estimates of size of recruiting year classes and current Fs for older year classes based on survey cruise VPA relationships	Commercial age/length frequencies are reviewed; F from earlier analyses reviewed relative to current cohort analyses; commercial landings by market categories reviewed
Haddock Gulf of Maine Georges Bank	Beverton and Holt yield per recruit model used to choose range of Fs considered in assessment. Also evaluation of effects of size at entry	Good historical yield model—useful in evaluating long-range potential	Analyses available	Stock-recruitment model investigated but not developed enough to use explicitly; the frequency of strong year classes relative to spawning stock size has been evaluated	Analysis available	Commercial age/length frequencies are reviewed; F from earlier analyses reviewed relative to current cohort analyses; commercial landings by market categories reviewed

Stock	*Yield per recruit*	*Equilibrium surplus production models*	*Virtual population analyses (VPA)*	*Stock-recruitment model considerations*	*Projections based on catch equation*	*Evaluation of relative stock abundance*
Pollock Nova Scotia Gulf of Maine	Beverton and Holt yield per recruit model used to choose range of Fs considered in assessment. Also evaluation of effects of size at entry	None	Available but based on limited aging	None	Current Fs estimated from survey—VPA relationships. Recruitment possibilities are chosen relative to historic year-class sizes	Commercial catch per unit effort and survey cruise trends evaluated
Redfish Gulf of Maine	Currently consider YPR analysis from Nova Scotia shelf stock	A model in use with Walter's (1976) procedure for non-equilibrium situation	None	None	None	Survey indices used; commercial catch/effort evaluated; survey and commercial length frequencies evaluated
Silver hake Gulf of Maine	See cod, Gulf of Maine. Model has also been used in conjunction with VPA estimates to calculate maximum sustained yield	A model available that is useful in evaluating long-range potential	Analysis available	See cod, Georges Bank	See cod, Georges Bank, but data base stronger	Survey indices used; commercial catch/effort evaluated; survey and commercial length frequencies evaluated. Pre-recruit survey indices used
Silver hake Georges Bank	See cod, Gulf of Maine. Model has also been used in conjunction with VPA estimates to calculate maximum sustained yield	See cod, Georges Bank	Analysis available	See cod, Georges Bank	See cod, Georges Bank, but data base stronger	Survey indices used; commercial catch/effort evaluated; survey and commercial length frequencies evaluated. Pre-recruit survey indices used
Silver hake Southern New England, Middle Atlantic	See cod, Gulf of Maine. Model has also been used in conjunction with VPA estimates to calculate maximum sustained yield	See cod, Georges Bank	Analysis available	See cod, Georges Bank	See cod, Georges Bank, but data base stronger	Survey indices used; commercial catch/effort evaluated; survey and commercial length frequencies evaluated. Pre-recruit survey indices used
Red hake Georges Bank	See cod, Gulf of Maine	None	Analysis available	None	See cod, Georges Bank	Commercial catch per unit effort not available; survey indices reviewed
Red hake Southern New England, Middle Atlantic	See cod, Gulf of Maine	See silver hake, Gulf of Maine	Analysis available	Qualitatively related to results of VPA analysis	See cod, Georges Bank	Commercial catch per unit effort not available; survey indices reviewed

Stock	*Yield per recruit*	*Equilibrium surplus production models*	*Virtual population analyses (VPA)*	*Stock-recruitment model considerations*	*Projections based on catch equation*	*Evaluation of relative stock abundance*
Yellowtail flounder Georges Bank	See cod, Gulf of Maine. Ricker model also used	See cod, Georges Bank	Very preliminary analysis available	Qualitative evaluation used	Yes, using Equations (31) and (32)	Commercial catch age compositions and catch per unit effort used; both total and pre-recruit survey catch rates used
Yellowtail flounder* Cape Cod plus southern New England, Middle Atlantic	See cod, Gulf of Maine. Ricker model also used	See cod, Georges Bank (for Southern New England only)	Available only for early 1960s	Qualitative evaluation used; fit to Ricker stock recruitment is poor	None	Commercial catch age compositions and catch per unit effort used; both total and pre-recruit survey catch rates used. Except no survey index for Cape Cod or commercial catch per unit effort for Middle Atlantic
Other flounders	None	None	None except for very preliminary one for fluke	None	None	Overall survey trends and changes in size composition reviewed relative to historical catches
Mackerel	See cod, Gulf of Maine	Walter's (1978) model where recruitment modeled as an impulse has been applied	Analysis available	Qualitatively only	See silver hake, Georges Bank	See redfish, Gulf of Maine
Sea herring Gulf of Maine	See cod, Gulf of Maine, and see silver hake, Gulf of Maine	None	Analysis available	Qualitatively only; minimum stock size concept used	Projection based on qualitative estimates of size at age 3 of each year class in the fishery	Viable commercial indices not available; survey indices of low precision
Sea herring Georges Bank, Middle Atlantic	See cod, Gulf of Maine, and see silver hake, Gulf of Maine	See cod, Georges Bank	Analysis available	Qualitatively only; minimum stock size concept used	Projection based on qualitative estimates of size at age 3 of each year class in the fishery	Viable commercial indices not available; survey indices of low precision
Sea herring Nova Scotia	See cod, Gulf of Maine	None	Analysis available	None	Projection based on qualitative estimates of size at age 3 of each year class in the fishery	Viable commercial indices not available; survey indices of low precision

*Considered as two stocks but currently managed together

Stock	*Yield per recruit*	*Equilibrium surplus production models*	*Virtual population analyses (VPA)*	*Stock-recruitment model considerations*	*Projections based on catch equation*	*Evaluation of relative stock abundance*
Loligo squid	Based on modification of Ricker's formulation	A model developed using yield per recruit combined with several hypothetical S-R curves	Preliminary analysis based on lengths	Used qualitatively	None	Commercial catch per unit effort and survey trends followed; population estimate of minimum biomass by areal expansion; length frequencies examined
Illex squid	Based on modification of Ricker's formulation	A model developed using yield per recruit combined with several hypothetical S-R curves	Preliminary analysis based on lengths	Used qualitatively	None	Commercial catch per unit effort and survey trends followed; population estimate of minimum biomass by areal expansion; length frequencies examined
Other finfish	No, except for butterfish	No, except for river herring and butterfish	No, except for very preliminary one for butterfish	None	None	Survey cruise trends followed; commercial length frequencies reviewed; commercial catch rate for river herring reviewed
Total finfish plus squid	None	A Schaefer yield model in use	None	Qualitatively only	None	Survey trends followed and used with equilibrium yield model to assist in assessing current conditions
Surf clams	Beverton and Holt model used to evaluate size at entry	None	None	None	Catch relative to survey cruise indices used to evaluate F and the corresponding catch	Survey cruise trends followed; commercial and survey length frequencies reviewed
Ocean quahogs	None	None	None	None	None	Survey cruise trends evaluated
Northern shrimp	See cod, Gulf of Maine; Ricker method also used	None	None	None	F is estimated from state of Maine inshore survey	Survey cruise trends evaluated. Length frequencies of survey and commercial catches evaluated

Nature and Adequacy of the Physical Data Base

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Introduction

This review is focused on the nature of the synoptic and climatic variability of the ocean and atmosphere and the adequacy of the meteorological, physical oceanographic, and hydrological data bases for resolving these variations. The primary emphasis is on conditions in the important fishing grounds of the Northwest Atlantic that lie shoreward of the Gulf Stream between Cape Hatteras and the Grand Banks.

The major atmospheric and oceanic scales of variability are reviewed briefly in the next section, where it is shown that the sampling requirements for resolving climatic variations are dictated largely by the more energetic quasi-geostrophic eddies of higher frequency. The sources of physical data for the area of interest are reviewed, and their adequacy for describing and modeling the circulation of the area are examined critically in the section titled "Adequacy of the Physical Data Base." Surface meteorological data, surface and subsurface oceanographic data, streamflow, precipitation, and ice cover are considered. Both archived data and current data products, including those derived from satellite imagery, are discussed. Additional information on these data products is included in Appendix A. An example of the data requirements for a relatively advanced circulation model is given in the section "Circulation Model Data Requirements." The last section, "Final Remarks," contains a few major conclusions from the review.

Scales of Variability

The kinetic energy spectra of the ocean and atmosphere exhibit scales of variability ranging from small-scale turbulence (minutes or less) to climatic variability on time scales of ice ages and longer. The focus of this workshop on the problem of climate and fisheries suggests a primary emphasis be placed on the data requirements for resolving the variability on the shorter climate time scales of months to years. However, to place those scales of variability in perspective, we will review the characteristics of the higher and lower frequency portions of the spectrum as well.

Figures 1 and 2 show examples of atmospheric and oceanic spectra. Figure 1 is a surface wind speed spectrum computed by Oort and Taylor (1969) from 5 years of hourly data taken at Caribou, Maine. Figure 2 shows spectra of current speed from two sites in the Middle Atlantic Bight, taken from a paper by Beardsley et al. (1976). Site A is in shallow water (12-m depth) just off the New Jersey Coast (39°28N, 75°15W). Data are from a depth of 5 m. Site D is located on the continental rise (2640 m) south of Cape Cod (39°20N, 70°00W). The spectrum is from observations at 100 m. Using these spectra as a guide, the variance can be divided into three general bands: (1) high-frequency variations with periods around 1 to 2 days or less; (2) quasi-geostrophic eddies, with periods of a few days to a few months; and (3) climate variations with periods longer than a few weeks. The high-frequency end of the climate band overlaps the

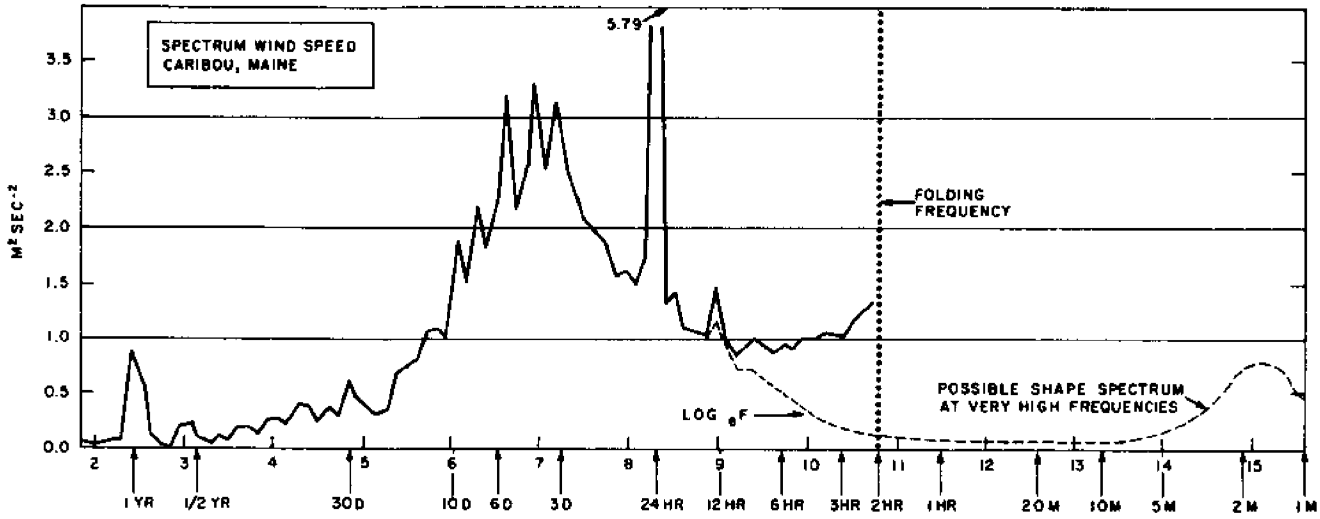

Figure 1. Spectrum of surface wind speed for Caribou, Me. (from Oort and Taylor, 1969).

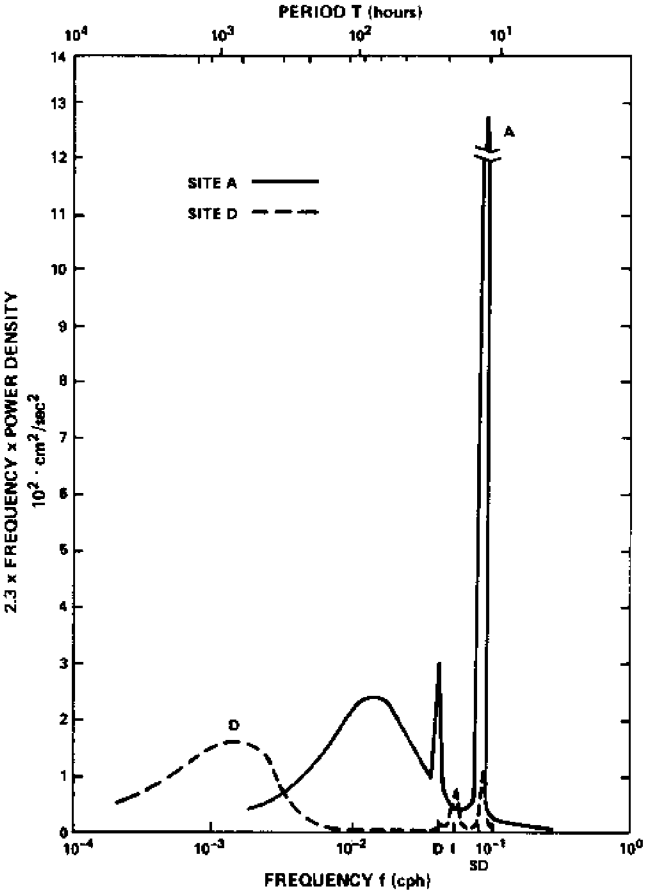

Figure 2. Spectra of currents in the Middle Atlantic Bight. Site A is located at 39°28N, 75°15W. Site D is located 39°20N, 70°00W. Adapted from Beardsley et al. (1976). The letters under the frequency axis are D for diurnal, I for inertial, and SD for semidiurnal.

frequency range of the oceanic quasi-geostrophic eddies, but, as will be seen from the subsequent discussion, there is normally a difference of spatial scales, i.e., the climate anomalies of interest will generally be of much larger spatial scale than the oceanic eddies.

High-Frequency Variations

Although a detailed description of this class of phenomena is of minor interest in the context of this review, the integrated effect over a period of time may be important, and therefore cannot be ignored in the more sophisticated dynamic modeling efforts. In the highest-frequency range of an hour or less are those processes which determine the vertical microstructure of the upper ocean: turbulence, and surface and internal waves. These motions are often assumed to be controlled by larger-scale phenomena and are parameterized in dynamic circulation models. Acquisition of data describing these motions and associated fluxes may require specially designed instrumentation and observational arrays over a limited time-space domain.

Longer period variations in the range of an hour to a day consist largely of tidal and inertial currents and changes in the vertical temperature profile due to the diurnal insolation cycle. Figures 1 and 2 show significant energy in this frequency band.

Although the characteristics of these oscillations must be described and understood in order to model their integrated effect over an extended period of time, it may not be necessary to routinely observe the details of the motion.

Quasi-geostrophic Eddies

The most energetic portion of both atmospheric and oceanic spectra lies between periods of a few days to a few months. The peak energy in the atmospheric spectrum is concentrated at the high-frequency end of this band and reflects the synoptic scale quasi-geostrophic eddies, with periods of around 5 days and spatial scale on the order 1,000 km. These synoptic variations in wind, temperature, and humidity are the dominant factors in modulating the sea-air fluxes of momentum and energy, and are the chief forcing mechanism for inertial and subtidal currents. The broad variance maximum associated with these disturbances is the dominant feature of the atmospheric spectrum, and is also clearly shown in the shallow water spectrum from nearshore Site A.

The deeper ocean quasi-geostrophic eddies exhibit a variance maximum at longer periods, of weeks to months, as illustrated by the Site D spectrum.

Most of the information on oceanic eddies has been obtained during the past decade. Analysis of mid-ocean data from the Mode I area (Richman et al., 1977) indicates significant kinetic energy associated with eddies having periods of 50 to 120 days, a result consistent with the temperature spectrum computed by Wunsch (1972) from data taken in the thermocline near Bermuda. Coherence between different moorings in the Mode I area indicates eddy sizes of the order of 100 km.

The data from Site D shows spectral peaks at somewhat higher frequencies than those found off Bermuda and in the Mode I area (Rhines, 1973). Rhines speculates that the dominant period may be locally determined, e.g., a function of bottom slope.

Mesoscale oceanic eddies are traced most clearly in the vicinity of strong boundary currents, such as the Gulf Stream. These Gulf Stream eddies or "rings" have been described by a number of authors, including Lai and Richardson (1977), Kerr (1977), Mizenko and Chamberlin (1977), Cook, Bisagni, and Hausknecht (1976), and Gotthardt (1973). The summary that follows is largely derived from these sources.

Although rings form on both sides of the Gulf Stream, it is only the warm core rings on the shoreward side that sometimes move into the proximity of the fishing grounds of the continental shelf and slope. These anticyclonic eddies may be formed when a Gulf Stream meander pinches off, much as an oxbow lake forms from a river meander. Warm core rings are typically around 100 km across, and may extend downward 1,500 to 2,000 m. Typical current speeds are a few nautical miles per hour, with temperature differences between the eddy and the local environment of several degrees. About three warm core rings usually exist north of the Gulf Stream at any given time.

Most warm core rings form southeast or south of Georges Bank. Some are reabsorbed within a month or two after formation, but the majority survive for 5 to 7 months. They generally move westward, then southwestward, at an average speed of 2 to 5 nautical miles per day. Their track is generally confined to a rather narrow zone between the shallow water of the continental shelf and the Gulf Stream. Eventually, it is reabsorbed into the Gulf Stream off Cape Hatteras. Unfortunately, not all eddies behave in such a predictable manner.

The ocean presents a fundamentally more difficult observational problem than the atmosphere, since the variability is important down to much smaller horizontal scales, while the periods are much longer. Consequently, the design of a realistic climate monitoring network, which will extract the low-frequency climate variations from the more energetic geostrophic eddy fluctuations, is a challenging task.

Climatic Variations

Climate is now recognized as being continually variable on all scales of time. The spectra in Figures 1 and 2 are based on only a few years of data, and therefore cannot adequately portray climatic variability. The peaks that do appear in the atmospheric spectrum about half-yearly and yearly merely reflect the variance associated with the mean annual cycle. Mitchell (1976) has prepared a "rather idealized and subjective bird's-eye view" of the spectrum of climatic variability that spans all scales of time, from billions of years to a small fraction of a day, as shown in Figure 3. The dashed curves in the lower part of the diagram indicate the total variance from processes characterized by spatial scales less than those indicated. Mitchell's paper

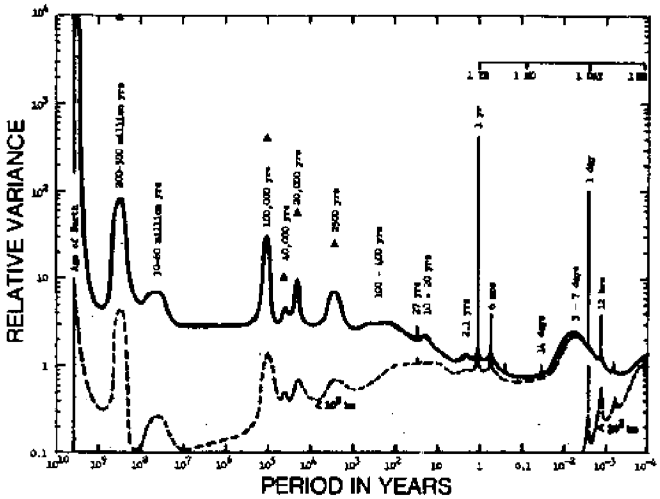

Figure 3. Estimate of relative variance of climate over all periods of variation. Dashed curves in lower part indicate the total variance from processes characterized by spatial scales less than those indicated. Strictly periodic components are represented by spikes. Triangles indicate variance of quasi-periodic features if they were represented as spikes. From Mitchell (1976). Reproduced by permission of Academic Press.

should be consulted for a discussion of causal mechanisms, a topic outside the scope of this review.

As noted earlier, our interest is primarily in the shorter period climatic fluctuations, which can be arbitrarily separated into two classes: (1) long-term (decadal-century) trends, and (2) monthly-interannual anomalies.

Long-Term Trends. As an example of long-term climatic trends, Figure 4, which was provided by Mitchell, shows the mean annual Northern Hemisphere temperatures since 1880. The major features of the time series are: (1) a period of warming, which ended around 1940; (2) a period of cooling, between 1940 and the mid-1960s; and (3) a period of relatively little change, from the mid-60s to the present.

Since 1880, the mean annual temperatures of the hemisphere have varied by only around 1°C; however, these long-term changes were by no means uniform. For instance, the warming during the period 1900 to 1940 was largely a high-latitude phenomenon, with mean winter temperatures in the latitude band 70 to 85°N rising a total of about 3°C (Budyko, 1977). The work of Van Loon and Williams (1976) clearly shows that decadal-scale trends arise as a result of changes in the large-scale features of the atmospheric circulation and are mostly regional in nature. Figures 5 and 6, reproduced from their paper, show isopleths of the slope of the regression line of winter temperatures for the two periods 1940 to 1954 and 1950 to 1964. These figures clearly illustrate the regional nature of the trends and the relatively large magnitude of the local changes. Namias (1972a) has demonstrated that the regional climate sometimes changes abruptly from one regime to another, rather

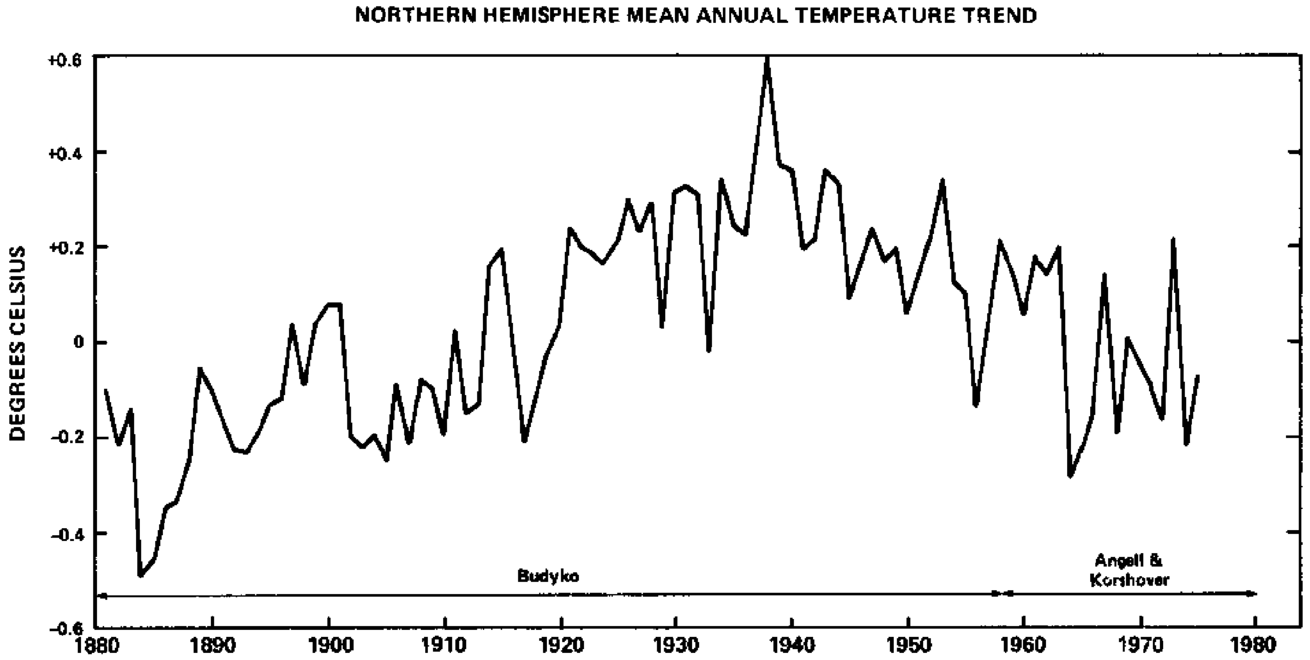

Figure 4. Northern Hemisphere mean annual temperature trend prepared by Mitchell from data of Budyko (1969) and Angell and Korshover (1977).

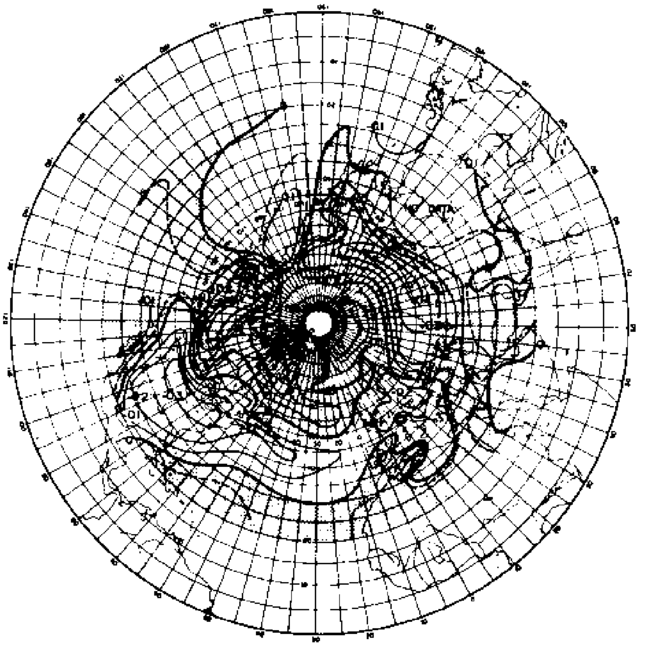

Figure 5. Isopleths of the slope of the regression line of mean winter temperature change for period 1940 to 1954 (°C/yr). From Van Loon and Williams (1976). Reproduced by permission of the American Meteorological Society.

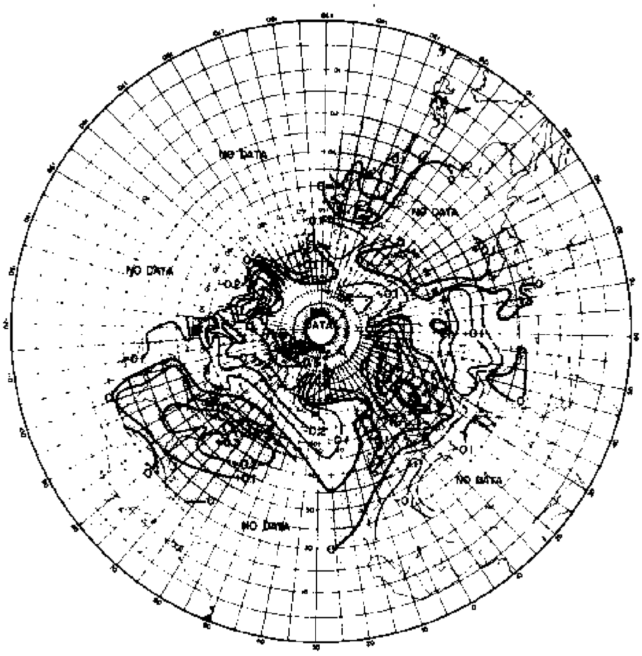

Figure 6. Same as Figure 5, except for the period 1950 to 1964.

than exhibiting a gradual trend over a number of years.

The tendency for most observations to be located over continental areas, coupled with the regional nature of these anomalies, leads to serious sampling problems. Since the mean hemispheric or global anomaly is a residual of large regional anomalies of opposite sign, the lack of resolution over the tropics and southern oceans leads to considerable uncertainty in estimated hemispheric or global temperature trends.

Monthly and Interannual Anomalies. Superimposed on these long-term trends are month-to-month and year-to-year variations in the ocean and atmosphere, often of large amplitude and large spatial scale. Figure 7 illustrates two strong and strikingly contrasting mean monthly temperature anomaly patterns over the United States during two successive winters. Although not as thoroughly documented, these anomalies extended well off the East

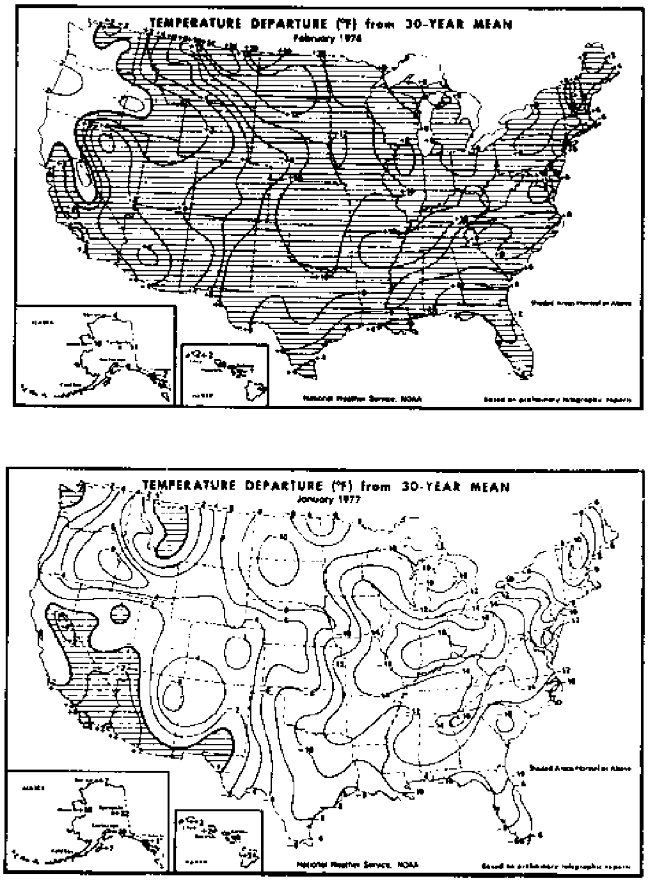

Figure 7. Departures from 30-year normal of mean monthly surface temperatures for the months of February 1976 and January 1977.

Coast during both months. For a more complete discussion of the weather during those months, see Dickson (1976) and Wagner (1977a).

The subnormal temperatures of January 1977 were preceded by several months of below-normal temperatures (Wagner, 1977b). The climate controls that lead to such persistent anomalies are not well understood, but it appears likely that large-scale, ocean-atmosphere interaction often plays an important role. The ocean represents a huge reservoir of heat and has a much longer "memory" of past climatic regimes than either the atmosphere or the land surface. Anomalies of sea surface temperature (SST) are the signatures of anomalies of sea-air exchange processes and fulfill the three criteria of Sawyer (1965) for effective climate control: (1) they are comparable in scale to the observed climatic anomalies (1,000 km), (2) they persist for at least 1 month, and (3) they reflect anomalous heat exchange rates of at least 50 langleys per day.

Since about 1950 it has been possible to construct mean monthly SST maps for the North Atlantic and North Pacific with a resolution sufficient to identify the large-scale anomalies and describe their general characteristics. The most comprehensive and definitive studies of these data have been carried out by Jerome Namias of the Scripps Institution of Oceanography. His results for the North Pacific indicate that SST anomalies are typically of large scale, with spatial coherence over 3,000 to 4,000 km (Namias, 1972b), and temporal correlations up to a year (Namias and Born, 1970). The anomalies tend to reach their extreme value during the cold season (Namias, 1973).

Due to a fundamental lack of time-series data on subsurface ocean variability, it is difficult to assess the depth structure of SST anomalies. However, Cushing and Dickson (1976) cite cases of extreme surface-generated thermal anomalies which extended to depths exceeding 100 m.

Adequacy of the Physical Data Base

The data required to describe the oceanographic, meteorological, and hydrologic processes of the northwest Atlantic area must be derived from a variety of sources. The degree to which these data are adequate to the needs of dynamic and empirical modeling varies according to parameter and specific application.

Atmospheric Data

Data requirements for general atmospheric modeling will not be discussed in this review, since this would involve an examination of the global meteorological data base. Rather, only the atmospheric data required to describe the local low-level meteorological fields will be considered.

Historical Data Base. The National Climatic Center (NCC), located in Asheville, North Carolina, is the central U.S. archive for global meteorological data. The surface data over the northwest Atlantic and vicinity are primarily of three types: (1) observations from fixed meteorological stations over both land and sea, (2) surface marine observations obtained from ships of opportunity, and (3) grid point values of surface meteorological fields routinely produced at the National Meteorological Center (NMC), Camp Springs, Maryland.

The distribution of the fixed U.S. surface stations over the area is shown in Appendix A (Figure A.1). These data are typically recorded every 1 to 6 hours, depending on the specific station. This temporal resolution, as well as the spatial distribution of stations, is more than adequate to resolve diurnal and synoptic variations over the United States, but the spatial resolution is inadequate over the northwest Atlantic. Although the situation is gradually improving with the deployment of an increasing number of meteorological buoys, it remains necessary to augment the fixed observations with merchant ship meteorological reports if the surface synoptic field is to be described adequately.

Appendix A shows the distribution of historical surface merchant ship observations over the area of interest (Figures A.2 and A.3). The meteorological and sea surface temperature data acquired by these ships of opportunity represent a large data base of uneven quality and geographical distribution. Observations for a particular area often extend back to the nineteenth century, usually with gaps during World Wars I and II. These data cluster in the coastal areas and along the major shipping routes of the world. They suffer from many sources of error, including poorly trained observers, poorly maintained instrumentation, and potentially unrepresentative observations, such as the use of ship intake temperatures as measurements of sea surface temperature. Nevertheless, when carefully edited and used in numbers sufficient to compute meaningful averages, these data have provided a wealth of information on the variability of the sea surface temperature field.

Ocean weather ships, while few in number, have provided valuable meteorological and oceanographic time series. Unfortunately, all U.S. weather ships have been phased out, to be replaced by meteorological buoys. Because of their more recent deployment, lack of year-round operation, and frequent changes of position, most of the buoys have yet to acquire a continuous time series of observations of significant length.

NCC and the collocated Naval Weather Service Detachment produce a number of data summaries derived from the basic surface observations. Among these products are the widely used "Summary of Synoptic Meteorological Observations" (SSMO) and a number of marine climatic atlases.

Operational Products. The National Meteorological Center (NMC) of NOAA, as well as the Fleet Numerical Weather Facility (FNWC) at Monterey, California, and the Air Force Global Weather Center (AFGWC) at Offutt Air Force Base, Omaha, Nebraska, produce a variety of operational meteorological products. NMC is one of three world meteorological centers, and it functions as the analysis center and central data collection point for the National Weather Service. The vast array of NMC products includes analyzed surface and upper air meteorological fields. The analyzed grid point data fields, which serve as initial conditions for dynamic prediction models, are themselves valuable sources of historical data. As an example, Sigurd Larson of the NMC Automation Division has produced a data set of surface geostrophic winds for the period 1946 to 1974, which consists of monthly means computed from individual 12-hourly pressure fields for the 65 x 65 FNWC Northern Hemisphere grid array.

Predictions of meteorological fields are generated by numerical weather prediction models for periods up to a few days. Experimental midrange dynamic predictions for periods up to 10 days have recently been initiated.

Monthly and seasonal outlooks of surface temperature and precipitation anomalies are also prepared which exhibit a modest degree of skill.

Physical Oceanographic Data

Because of the difference in the types and amounts of data available at the ocean surface compared with subsurface levels, it is convenient to discuss surface and subsurface data separately.

Surface Data. Ocean surface data can be divided into two classes: in situ measurements and data derived from remote sensors. Parameters of prime interest are temperature, salinity, current (or sea level), the radiation balance, and the sea-air fluxes of sensible heat, water vapor, and momentum (surface stress).

Sea surface temperature. Prior to the early 1970s the sea surface temperature (SST) field was defined primarily from merchant ship data, which were discussed under "Atmospheric Data." Statistics on the distribution of these data over the northwestern Atlantic are included in Appendix A.

Special note should be made of an SST data set particularly oriented to the area of interest. It consists of the U.S. Coast Guard airborne radiation thermometer surveys of United States Atlantic coastal waters, originally begun in 1962 as a joint effort with the Bureau of Sports Fisheries (BSF) and NMFS (Deaver, 1975). These surveys are conducted, weather permitting, over a 4-day period during the middle of each month by personnel of the Coast Guard Oceanographic Unit. The same flight tracks are flown each month unless altered to avoid bad weather. An isotherm chart is produced after the completion of each survey. Figure 8 is an example of the detailed analyses that can be made from these charts.

A new source of SST data became available with the successful orbiting of the NOAA-2 satellite in October 1972. The polar-orbiting, sun-synchronous satellites in the NOAA series carry two sensors capable of providing estimates of surface water temperature (Kniskern and Thompson, 1975).

The first of these is the Very High Resolution Radiometer (VHRR) which has given oceanographers a huge amount of useful data. The application of these data will be discussed in the section "Northwest Atlantic Surface Synoptic Analysis."

The second sensor is the Scanning Radiometer (SR), which is essentially the same sensor that was aboard earlier spacecraft (Kniskern and

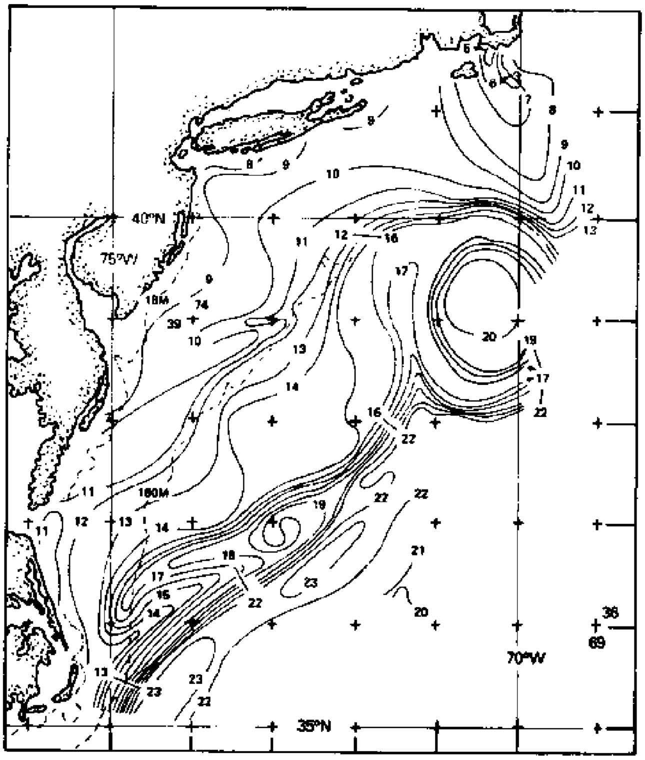

Figure 8. Sea surface temperatures as analyzed from ART flights of November 17 and 20, 1976. The dashed ring indicates an eddy position inferred from NOAA-5 VHRR imagery of November 26, 1976 (from Morgan and Deaver, 1976).

Thompson, 1975). One channel of the SR senses energy in the visible spectrum with a resolution of 4 km. The other channel senses energy in the infrared "window" with a resolution of 7.5 km. Global fields of sea surface temperature are routinely derived from these data by the National Environmental Satellite Service (NESS) of NOAA using the fully automated computer procedure Global Operational Sea Surface Temperature Computation (GOSSTCOMP). The basic product is a daily set of 5,000 to 6,000 values of SST, each derived from measurements over roughly a 100-km^2 area, covering both hemispheres. In addition to the individual observations, NESS prepares a globally analyzed SST field as a derived product. Both the basic observations and the analyzed fields, as well as other satellite products, are routinely archived by the Satellite Data Services Branch (SDSB) of NCC. During 1974, 1,640,654 observations were produced, with a global mean difference from ship reports for individual maps ranging from -0.90°C to +0.39°C and RMS deviations varying between 1.67°C to 2.23°C (Kniskern and Thompson, 1975).

Because of calibration problems in the basic satellite SST data and shortcomings in the objective routines for producing the analyzed fields, it is our judgment that the full potential of these products has yet to be reached. In the long run, these data offer the only real hope for adequately defining the sea surface temperature fields over the tropical and southern oceans.

Surface current and salinity. Direct observations of surface current and salinity are sparse, intermittent, and inadequate for describing deviations and in some cases even the "normal" situations in more than a general sense.

Information on surface currents can be derived from accurate sea level observations. Such data have been limited to observations from tide gage stations (see Table 1). Wyrtki (1974) in his studies of the circulation of the tropical Pacific has demonstrated the value of tide station data.

Table 1. National Ocean Survey (NOS), NOAA, coastal tide stations along the northeast U.S. coast for which 6-min tidal height measurements are available.

1. Eastport, Me.
2. Bar Harbor (Mt. Desert Island), Me.
3. Portland, Me.
4. Portsmouth, N.H.
5. Boston (Appraiser's Stores), Mass.
6. Nantucket (Nantucket I.), Mass.
7. Woods Hole (Woods Hole Oceanographic Institution), Mass.
8. Newport (U.S. Naval Training Station), R.I.
9. New London (State Pier, Thames River), Conn.
10. Montauk, N.Y.
11. Sandy Hook (Fort Hancock), N.J.
12. Atlantic City, N.J.
13. Cape May, N.J.
14. Lewes (Breakwater Harbor), Del.
15. Indian River Inlet (USCG Station), Del.
16. Ocean City, Md.
17. Kiptopeake Beach (Ferry Terminal), Va.
18. Sewells Point (Hampton Roads), Va.
19. Little Creek, Va.
20. Avon, N.C.
21. Morehead City (Atlantic Beach), N.C.

From material compiled by the Working Group on Atmospheric Forcing in the Middle Atlantic Bight.

Recent work by Huang et al. (1978) demonstrates that the precision of sea level height measurements obtained from the radar altimeter on board the GEOS-3 satellite is sufficient to provide valuable information on the temporal and spatial variations in the Gulf Stream front and associated eddies. This demonstration of the feasibility of obtaining useful sea level measurements from space lends added interest to the launching this year of the experimental satellite SEASAT-A. This will place into orbit an instrument complement fully dedicated to oceanic requirements (surface winds, waves, SST, sea level, ice cover), and offers all weather monitoring at the ocean surface, utilizing data from the microwave region (SEASAT-A Project Development Plan, 1977). The SEASAT-A instrument for obtaining sea level measurements is a nadir-looking altimeter with a very short pulse signal that measures the displacement between the satellite and the ocean surface to a processed accuracy of 10 cm every 18 km and the RMS roughness of that surface to about 1 m. It is hoped that these data will be adequate for evaluating the surface velocity of the more intense current systems, such as the Gulf Stream, as well as providing information on tsunamis, storm surges, and ocean tides.

Surface currents estimated from ship drift observations represent a data base of uncertain quality. In their analyses of the mid-Atlantic region, Williams and Godshall (1977) found the ship drift data available from NODC to be useful for the study of the long-term mean seasonal surface currents at a resolution of 1/2°, but the number of observations was deemed insufficient for determining reliable mean monthly values, let alone for evaluating the differences between individual months or seasons.

Surface exchange processes. A knowledge of the energy and momentum exchange across the sea-air interface is of fundamental importance in understanding the processes leading to temperature and circulation changes within the ocean, and is an essential boundary condition for dynamic modeling. Sea-air exchange processes are not directly measured, but must be computed by empirical relationships involving sea surface and atmospheric parameters. Consequently, the accuracy of the computations depends on the adequacy of the empirical relationships as well as on the quantity and quality of the data.

Evaluation of momentum flux (surface stress) requires values of low-level wind velocity. Bakun (1973) has demonstrated that simple indices can often be used to infer the intensity of stress-induced motions, i.e., upwelling and Ekman transport, directly from the surface pressure field, i.e., the surface geostrophic wind field.

Evaluation of sensible and latent heat fluxes requires values of low-level wind speed, SST, and low-level atmospheric temperature and vapor pressure. The radiation balance at the surface is an important additional component of the ocean heat budget. Computation of this quantity requires knowledge of SST, surface albedo (which in turn may require knowledge of ice cover and condition), and cloud cover. Cushing and Dickson (1976) credit a change in solar radiation at the ocean surface resulting from changes in cloudiness as being the reason for an important change in the timing and duration of oceanic production in the European arctic and subarctic during the period 1948 to 1965.

For data on cloud cover over the ocean, ship weather observations have served as the primary source. Visible and IR satellite imagery are a potentially valuable source of cloud information, but only the Air Force Global Weather Central now produces cloud analyses that make use of satellite data.

Bunker and Worthington (1976) computed the sea-air fluxes of momentum and energy over the North Atlantic Ocean. Using 8 million ship weather reports, they obtained values for 66 10° squares for each month from 1941 through 1972. They also derived mean monthly and annual values for this period for 500 smaller areas. The reader is referred to their paper for a discussion of the empirical relationships used and the results of the computations. Their monthly time series can, in principle, be extended to the present time, although the 10° resolution may be rather coarse for some applications.

Northwest Atlantic Surface Synoptic Analyses. The use of VHRR imagery to observe the ocean surface thermal field allows, for the first time, the near real time construction of detailed semi-quantitative synoptic maps of the surface temperature and current fields over the northwest Atlantic. This new era in ocean analysis began with the launch of the improved TIROS Operational Satellite (ITOS D), subsequently named NOAA-2, in October 1972. As noted earlier, this and subsequent satellites in the NOAA series carry a sensor of particular significance to oceanography, the Very High Resolution Radiometer (VHRR). The VHRR instrument is sensitive to energy in the visible spectrum, 0.6 to 0.7 ℓ m, and the IR window, 10.5 to 12.5 ℓ m (Kniskern and Thompson, 1975). The resolution of 0.9 km in both the visible and the TR sensors allows observation of oceanographic features not previously discernible by satellite remote sensing. Data coverage is limited to approximately 3,600 km of a readout station. The Wallops Island, Virginia, Command and Data Acquisition (CDA) station supplies data for the northwest Atlantic. Because of the large variation in surface temperatures between water masses in this area, these data can be used to map and follow discrete surface thermal features, such as warm core eddies, for extended periods of time. Figure 9, a NOAA-3 imagery taken from Knis-

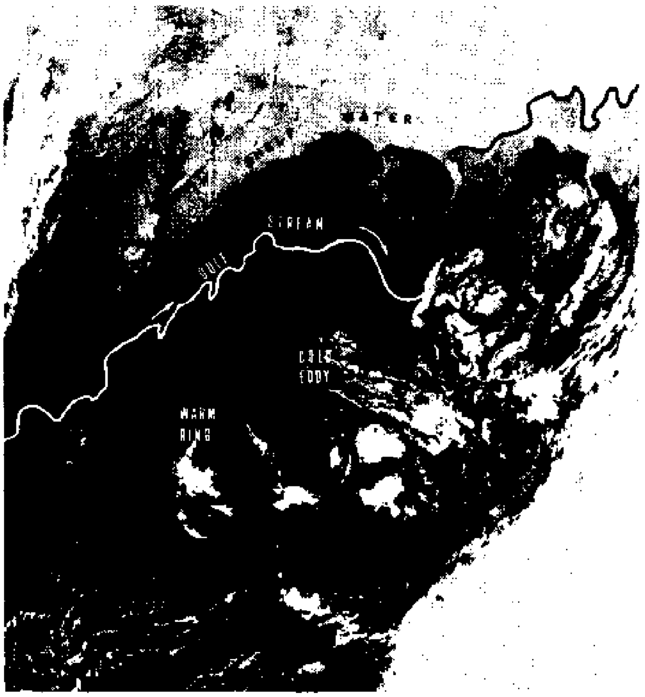

Figure 9. NOAA-3 VHRR IR image of water structure off the U.S. East Coast, April 28, 1974.

kern and Thompson (1975), is a good example of the kind of information that is now available on a routine basis.

Such features as the movement and meandering of thermal fronts, the movement of eddies, the fluctuation in size of upwelling areas, the expansion and contraction of large warm- or cold-water regions, and the advection of tongues of cool or warm water lend themselves to description. Rather than quantitative, however, the methods of analysis and interpretation of the VHRR data alone consist largely of pattern recognition.

Two factors hinder the acquisition of daily images of the sea surface. These are the presence of clouds, particularly during the late spring and early summer, and the weak or nonexistent surface temperature gradients between water masses that often exist during summer. Future satellites, such as SEASAT-A, which carry a radar altimeter for all weather measurement of sea surface heights, may prove a valuable new aid in identifying and tracking Gulf Stream meanders and the stronger eddies. It has also been suggested that color imagery may be of value in identifying circulation features, and data from future satellites that carry color scanners, e.g., the Coastal Zone Color Scanner (CZCS), may provide useful information on water mass boundaries during periods of uniform surface temperatures.

Using real time satellite data, various service organizations routinely issue the following operational products for specialized and general user groups:

(1) NOAA/NESS Gulf Stream Analyses (Figure 10). This chart, also from Kniskern and Thompson (1975), should be compared with the VHRR image for the same time shown in Figure 8. The chart depicts all the water masses and associated fronts off the East Coast of the United States. It usually represents a composite of several satellite images, since the area is seldom cloud-free.

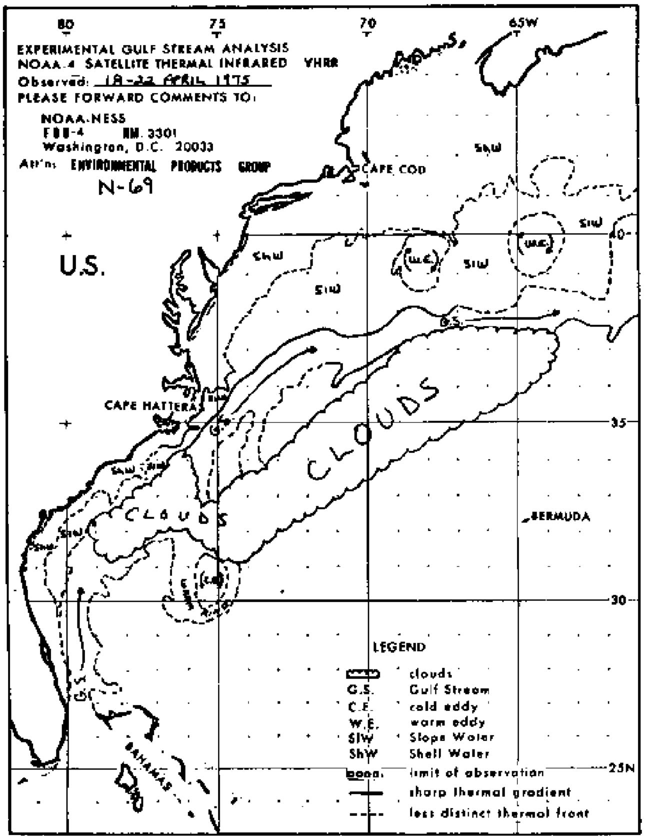

Figure 10. NOAA/NESS Experimental Gulf Stream Analysis.

(2) U.S. Naval Oceanographic Office Experimental Ocean Frontal Analyses (Figure 11). This analysis shows the surface temperatures as well as the boundaries of the water masses that lie off the United States East Coast. Analyses are prepared and disseminated weekly in two sections: Nova Scotia to Cape Hatteras, and Cape Hatteras to the Straits of Florida. Frontal locations, eddies, and areas of lesser thermal contrast are determined from VHRR imagery. The prior week's merchant ship reports, as well as bathythermograms that may be available, are used to determine water mass temperatures. The analyses are prepared primarily for

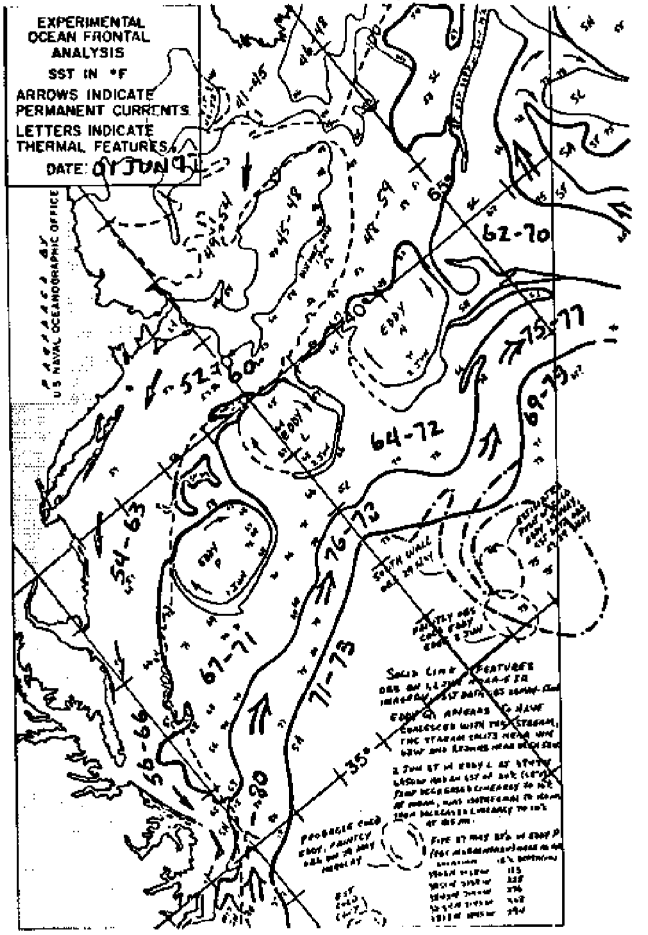

Figure 11. U.S. Naval Oceanographic Office Experimental Ocean Frontal Analysis.

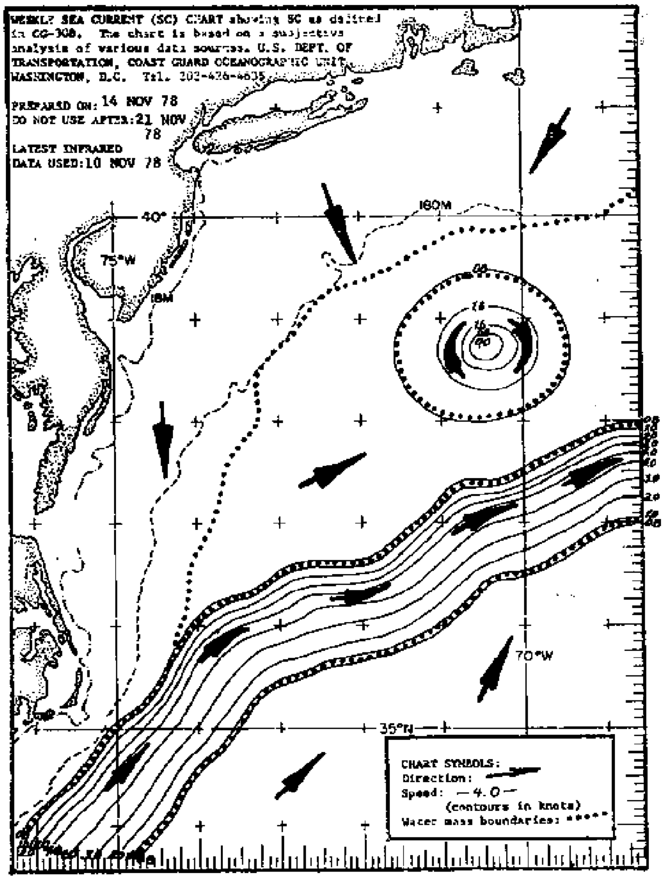

Figure 12. U.S. Coast Guard Current Analysis.

U.S. Navy fleet commands and agencies. The charts are also provided to government organizations, academic institutions, and government contractors.

(3) U.S. Coast Guard Current Analysis (Figure 12). The U.S. Coast Guard has taken the surface information one step further to produce a current analysis. All available data — bathythermographs, sea surface temperature from ships, and ART imagery — are used to supplement the satellite data in preparing these analyses, which are telecopied to Rescue Control Centers and mailed to other users.

Subsurface Oceanographic Data. The lack of adequate data for defining the subsurface mass and current fields for either modeling or documenting long-term climate variations represents the major physical data deficiency over the northwest Atlantic.

The National Oceanographic Data Center (NODC), Washington, D.C., serves as the central archive for these data. However, a higher percentage of subsurface oceanographic data is likely to be found at local institutions than is the case for surface oceanographic and atmospheric data. For example, at the inception of their study of the mid-Atlantic region (38°N to 41°N) Williams and Godshall (1977) found approximately 2,500 salinity-temperature-depth (STD) and Nansen casts to be available for the area from NODC. Subsequent efforts to supplement these data resulted in the location of 5,300 additional casts at various institutions, which were then added to the NODC files.

Subsurface current meter data are generally archived at NODC in the various formats in which they were submitted by individual investigators, which makes comprehensive use of these data difficult. A considerable amount of the data from the mid-Atlantic region has, however, been put into a common format by NOAA's Marine Ecosystems Analysis (MESA) Project Office.

The surface and seabed drifter file of NODC represents a source of data on surface and bottom currents. Comprehensive studies of these data in their original form have been made by Bumpus and Lauzier (1965) and Norcross and Stanley (1967).

Table 2, taken from Williams and Godshall (1977), summarizes the data available at NODC for the mid-Atlantic area (38°N to 41°N between the coast and the 2,000 meter isobath). A further inventory of NODC data over the northwest Atlantic is included in Appendix A.

Regarding the adequacy of the mid-Atlantic data, Williams and Godshall reached the following conclusions:

(1) The MBT and XBT data constitute by far the largest source of subsurface temperature data, and are useful after careful editing. Significant mean temperature differences were found between these data sets, as well as between these data and the STD Nansen cast data. These differences are believed to result from large natural variability, including possible long-term trends in continental shelf temperatures and temperature gradients; sampling biases; instrumental biases and random errors; and errors in reporting or processing procedures, leading to, for example, position, date-time, and reference temperature errors. Because of these differences, the STD Nansen cast data, which are inherently more accurate than the MBT and XBT data, were used for subsequent analyses.

(2) The STD Nansen data are adequate for identifying the major water masses of the area and for delineating their approximate boundaries. They are also adequate for documenting seasonal, but not monthly, means and variabilities in most cases. The number of these observations is not sufficient for delineating the shelf-slope water front.

(3) Salinity data for most of the mid-Atlantic region cannot be used to reliably describe the physical processes taking place, a problem compounded by year-to-year variability and by the fact that intraseasonal variability is often larger than mean seasonal variability.

(4) For summer and fall, the number of observations of specific volume anomaly is inadequate for determining the mean fields of mass and pressure at a spatial resolution of less than about 100 km. Hence, the historical data base is of limited use in objectively estimating mean seasonal geostrophic currents in the mid-Atlantic region. Its use as input to circulation models, other than those employing the vertically integrated mass fields, is also limited because of the poor spatial and temporal distributions of the data. Geostrophic computations could best be made from these data on a quasi-synoptic (cruise-by-cruise) basis, rather than from seasonal averages.

Table 2. Oceanographic data for the mid-Atlantic region available at NODC.

Observation system	*No. of casts or observations*	*Measured quantity*	*Expected accuracy*	*Remarks*
Mechanical bathythermograph (MBT)	28,000	Temperature (T)	On the order of ±0.5°C and ±3 m	Cover period 1944 to present; accuracy highly dependent on calibration methods and handling; being replaced by XBT.
Expendable bathythermograph (XBT)	10,000	Temperature (T)	± 0.1°C ± 2 m	Cover period 1962 to present; repeatability of the digitized XBT record is ± 0.2°C and ± 2 m.
Nansen cast	7,764	Temperature (T) Salinity (S) Oxygen (O_2) Nitrate (NO_3) Phosphate (PO_4) Silicate (S_iO_3)	± 0.02°C ± 0.02% ± 0.04 ml/l ± 5% ± 10% ± 8%	NODC does not distinguish between temperatures and salinities from Nansen casts or from STD sensors.
Electronic salinity-temperature-depth (STD) sensor		Temperature (T) Salinity (S)	± 0.02°C ± 0.03%	Accuracies approximate; depend on manufacturer.
Subsurface current meter	133	Current speed (V) Current direction (θ) Pressure (P)	± 10% ± 5° ± 1%	Accuracies depend on manufacturer and mooring configuration; accuracies given here are for the Aandera meter.
Surface currents from ship drift	75,661	Ship drift		Cover period 1850 through 1974; relies on large numbers of observations to reduce error.

(5) The number and duration of direct current measurements are inadequate for resolving reliably the time and space scales of motion in the region, except in the New York Bight apex. In experimental studies, simultaneous measurements of current and wind have seldom been made. The wind data used in such studies have been obtained at land stations or other fixed sites many miles away and at sampling rates incompatible with the current measurements. This lack of systematic approach to studies of ocean response to atmospheric forcing precludes documentation of the spatial and temporal characteristics of the response of the ocean, and severely limits prediction modeling.

Fixed Oceanographic Stations and Standard Sections. The ideal ocean monitoring system would resolve the geostrophic "synoptic" eddy field, allowing the computation of the underlying climatic variability. This has neither been possible in the past, nor is it likely to be true in the foreseeable future, except possibly at the ocean surface. Assuming, however, that the more important climatic variations occur on a scale of 10^6-10^7 km^2 or larger, effective long-term monitoring can be accomplished by a relatively small number of carefully placed stations, provided they are occupied frequently enough to resolve the temporal variations arising from geostrophic eddies. This suggests an examination of data from the following fixed ocean stations and standard sections:

(1) Ocean Station Weather Ships. These platforms have provided valuable time series in the past, although only OWS "HOTEL" was stationed in the area of primary interest. The United States ships in the western North Atlantic have been phased out, leaving only the European ships in the eastern North Atlantic.

(2) Meteorological Buoys. These platforms, which may also be equipped to acquire subsurface data, are being deployed in western Atlantic coastal waters (see Appendix A). Records to date are short, usually with breaks, particularly during winter, and with changes in buoy positioning common.

(3) Standard Monitoring Sections. Figure 13 shows the series of standard monitoring sections off the East Coast of North America that have been occupied for a number of years. Sections 5, 6, and 7 were occupied approximately twice yearly from 1966 to 1976, mostly by weather ships on their return from ocean stations BRAVO, CHARLIE, DELTA, and ECHO. Occupation of these sections ceased with the discontinuation of the ocean stations.

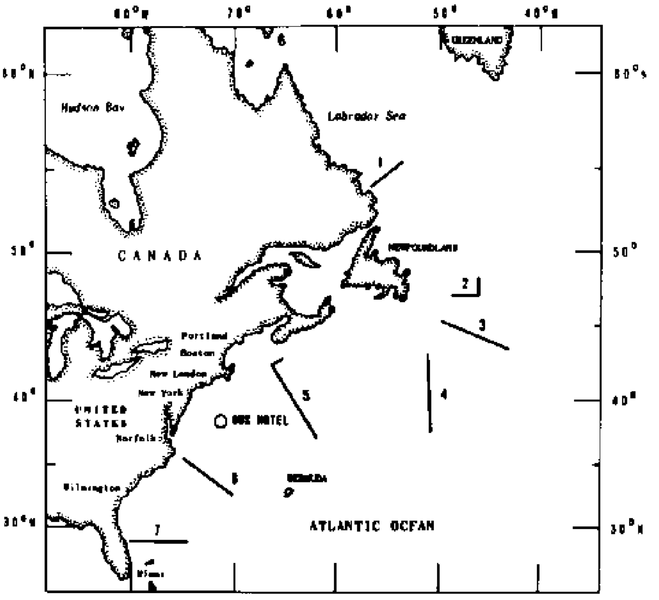

Figure 13. Standard Monitoring Sections.

Sections 1, 2, 3, and 4 have been occupied from 1964 to 1966 in connection with the international ice patrol activities of the U.S. Coast Guard, and are occupied mostly from April to July of each year. From sections 2, 3, and 4, respectively, 66, 69, and 36 individual sections are available.

In summary, 2, 3, 4 are the only sections still being occupied in the area of primary interest. Although occupation is less frequent than desired, it may be frequent enough to provide valuable data on climatic variability.

(4) NMFS/MARAD Ship of Opportunity Program. This relatively new program, begun in mid-1970, has a potential for providing valuable climatic data. Detailed information on the project can be found in the project annual reports (Cook, 1973, 1975, 1976; Cook and Hausknecht, 1977).

The program, conducted in support of the Marine Resources Monitoring Assessment and Prediction Program (MARMAP) of NMFS, involves the use of cadets from the Kings Point Maritime Academy to collect XBT data on board merchant ships operating along the East and Gulf Coasts of the United States. Since 1970, the Ship of Opportunity Program (SOOP) has expanded to include U.S. Coast Guard cutters and university research vessels.

The objective of this cooperative program is to identify and describe seasonal and year-to-year variations of temperature and circulation in the major current regimes of the western tropical Atlantic, Caribbean Sea, Gulf of Mexico, and western North Atlantic, utilizing various ships as relatively inexpensive platforms for data collection. Figure 14 shows the general ship tracks used in the SOOP Program, and Table 3 summarizes the number of transects obtained each year along these tracks.

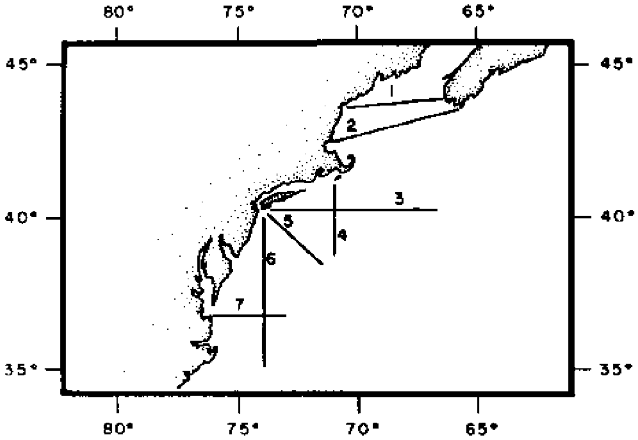

Fig. 1 - Western North Atlantic Transects

1 - Portland to Yarmouth
2 - Gloucester to Cape Sable
3 - New York to Mediterranean
4 - 71° west longitude
5 - New York to Deepwater Dumpsite 106
6 - New York to South America
7 - Norfolk to OWS Hotel

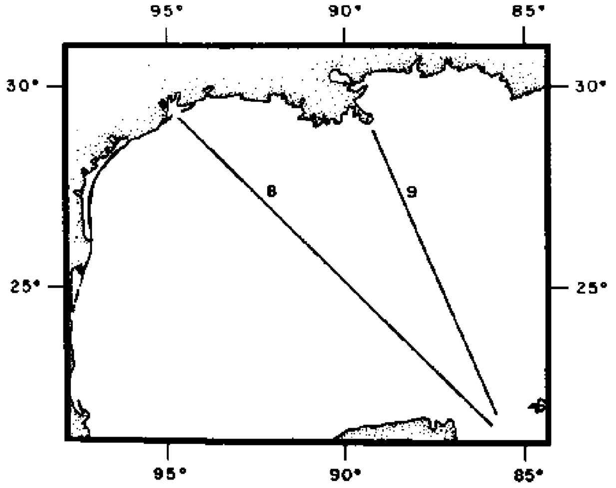

Fig. 2 Gulf of Mexico Transects

8 New Orleans to Yucatan Straits
9 Galveston to Yucatan Straits

Figure 14. NMFS/MARAD Ship of Opportunity Program (SOOP) Atlantic Transects.

Beginning in 1971, only four XBT systems were in operation (two out of New Orleans and two out of New York). At that time, XBT observations were made approximately 4 to 6 times daily for the entire voyage. The result was weak sampling in the near-shore and continental shelf areas. In order to provide more valuable data for research on fishery and shelf processes, the program was modified in 1973 to collect hourly XBT data for the first 24 hours into and out of all North American ports, and to cease the 4 to 6 daily observations in mid-ocean.

A program expansion began in 1974 with the purchase of two additional XBT systems annually, and continued until 1976, when it was terminated due to manpower and fiscal restraints.

Table 3. Number of SOOP XBT transects per year.

	1971	*1972*	*1973*	*1974*	*1975*	*1976*	*1977*
Gulf of Mexico	9	7	6	16	25	13	5
South Atlantic Bight	19	22	4	7	6	5	9
Middle Atlantic Bight				12	37	42	44
Gulf of Maine					14	13	15

NMC Operational Products. In addition to the routine collection of meteorological data, NMC receives bathythermograph (BATHY) and temperature/salinity (TESAC) subsurface data transmitted through the Global Telecommunications System (GTS) as part of the Integrated Global Oceanographic Station System (IGOSS) program. An inventory of reports received during 1976 and 1977, and the distribution of BATHY observations received during September 1977 are included in Appendix A. The data coverage is not adequate to definitively map the dynamic oceanic features of the entire northwest Atlantic, but it is sufficient for limited analyses in the Gulf Stream region, and for more extensive analyses in the POLYMODE area (27° to 33°N, 66° to 75°W).

Using these data, together with surface reports and satellite imagery, NMC has recently initiated two important new operational maps that portray the surface and subsurface thermal structure of the northwest Atlantic and northeast Pacific (Gemmill and DeRyke, 1977). The analyses are quantitative but less detailed and of lesser horizontal resolution than most of the ocean surface analyses discussed in the section "Northwest Atlantic Surface Synoptic Analyses."

The first of these maps is an experimental SST analysis for the western Atlantic (Figure 15) based on an average of approximately 800 surface ship and BATHY observations received over a 5-day period.

The second map consists of an analysis of the depth of the 17.5° isotherm, derived from BATHY, surface, and satellite data collected over a 30-day period (Figure 16).

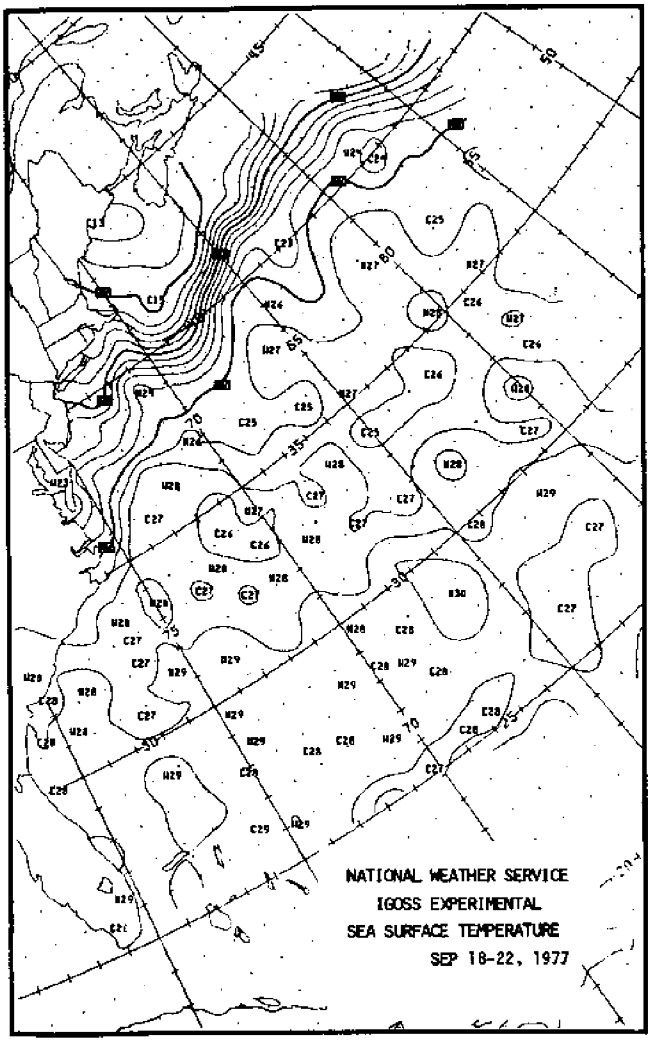

Figure 15. National Weather Service Experimental SST Analysis.

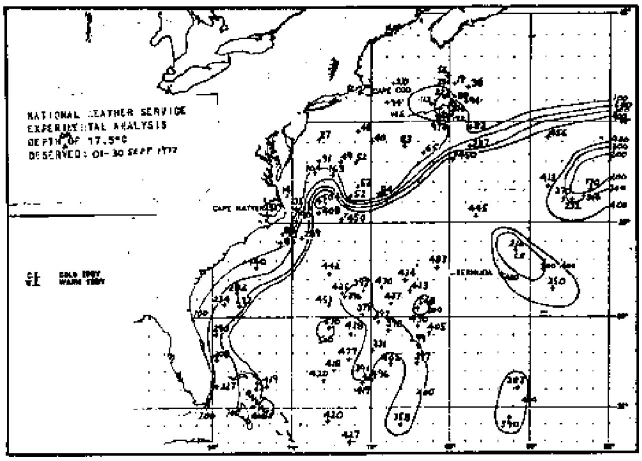

Figure 16. National Weather Service Experimental Analysis of the depth of the 17.5°C isotherm.

Hydrological Data

Abnormal precipitation and streamflow can result in significant disruption of the biological regime of bays and coastal areas, as evidenced, for instance, by the disruption of the Chesapeake Bay system that resulted from the huge freshwater inflow associated with the passage of Agnes in June 1972.

The major accumulation of river water on the shelf in the Middle Atlantic Bight occurs during the spring season. Ketchum and Keen (1955) estimate that 50 percent of the total annual discharge into the mid-Atlantic region occurs during the March-May period. Anomalously high flow, when combined with above-normal late winter and spring temperatures, as was the case in 1976, results in unusually stable stratification of the shelf waters during the spring and early summer.

The flow of all major United States rivers that discharge into the sea is measured a short distance above tidewater. Downstream gaging stations for the major rivers that discharge into the Atlantic south of Nova Scotia are listed in Table 4. The discharge of the St. Lawrence and its major tidewater tributaries, which may also be of importance to the physical oceanography of the northern portions of the area of interest, is also measured. Past data on United States rivers is easily available from the U.S. Geological Survey. Relatively accurate real-time estimates of streamflow are available from the National Weather Service.

Table 4. Downstream gaging stations for the major rivers discharging into the Atlantic between Maine and Florida.

River	*Station*
Penobscot	West Enfield, Me.
Kennebec	Bingham, Me.
Androscoggin	Auburn, Me.
Merrimak	Lowell, Mass.
Connecticut	Thompsonville, Conn.
Hudson	Green Island, N.Y.
Delaware	Trenton, N.J.
Susquehanna	Harrisburg, Penn.
Potomac	Washington, D.C.
James	Richmond, Va.
Roanoke	Roanoke Rapids, N.C.
Cape Fear	Lillington, N.C.
Pee Dee	Pee Dee, S.C.
Santee	Pineville, S.C.
Savannah	Clyo, Ga.
Altamaha	Doctortown, Ga.
St. Johns	DeLand, Fla.

From Discharge of Selected Rivers of the World, UNESCO, 1974.

Shipboard measurement of rainfall is notoriously difficult. Several methods have been proposed for estimating precipitation at sea (see, for example, WMO Report No. 442, 1976), but all attempts to date have met with only limited success. WMO Report No. 442 states:

> No method has been developed for the desired measurement of rainfall by all ships crossing the oceans such as would be required for the production of an ocean atlas of rainfall.
>
> The few available oceanic precipitation charts fall into two categories. The first category comprises charts which have been subjectively prepared using precipitation data from coastal and island stations and some subjective knowledge about the frequency of precipitation at sea. The second category of charts are those using the Sawyer-Tucker method based on the use of synoptic ship reports.

Recent developments in satellite meteorology encourage the view that it may be possible in the future to assess rainfall amounts over the sea from satellite observations. Among the more promising possibilities is the use of microwave brightness temperatures to estimate rainfall rate (Wilheit et al., 1975). Thus far, the measurements have been obtained from polar-orbiting satellites, which provide only two "snapshot" observations each day. Published mean monthly rainfall rates obtained from Nimbus-5 microwave data (Rao et al., 1976) are given only in terms of four rain-rate categories, and only for averages over 4° squares. Deficiencies in the maps are apparent, and the authors claim a reliability in absolute values of rain rate no better than a factor of two.

Ice Cover

Ice cover is a factor over the northern portions of the area of interest, i.e., the Gulf of St. Lawrence and Newfoundland coastal waters. Environment Canada has prepared a series of publications entitled "Ice Summary and Analysis for the Eastern Canadian Seaboard," which describes conditions over this area for each of the years from 1964 to 1973. Ice data were analyzed and correlated with relevant meteorological and oceanographic factors to produce the series of weekly charts contained in these publications. The principal source of the data was a series of aerial observations by personnel of the Atmospheric Environment Service, Environment Canada, supplemented by observations and helicopter flights from ice breakers. An ice atlas for this area is being prepared by Environment Canada.

An ice chart is prepared for operational purposes by the Ice Branch, Central Services Directorate, Environment Canada, three times weekly and is available by subscription. Data collected by specially equipped chartered aircraft, ice breakers, and merchant ships, together with NOAA VHRR imagery, are used in the construction of these charts.

Circulation Model Data Requirements

The nature and use of dynamic circulation models is discussed in another workshop review paper. However, it might be well to briefly note here an example of the data requirements of a relatively advanced dynamic model being developed for the mid-Atlantic region.

The model considered is being developed by Alan Blumberg and George Mellor of the Geophysical Fluid Dynamics Program of Princeton University. The description of the boundary conditions is based on material provided by Blumberg and Mellor, together with the position paper "A Prospectus for Ocean Circulation and Wave Analysis and Prediction Programs for the Middle Atlantic Bight and Gulf of Maine" prepared by the Working Group for Atmospheric Forcing in the Middle Atlantic Bight (AFMAB).

The model domain is currently defined by the northeast Atlantic coast, the zonal transect extending eastward from Hatteras and the meridional transect extending southward from Cape Cod (Figure 17). The horizontal resolution is 1/4°, representing 24 x 28 horizontal grid points. There are 20 grid points in the vertical, representing a relatively fine resolution on the shelf compared with that on the continental rise. Because the vertical spacing is smallest near the surface and the bottom, the mixed layer and thermocline are resolved, and the bottom layer is also crudely resolved on the shelf. The prognostically calculated variables are velocity, temperature, salinity, turbulent kinetic energy, and the turbulent macroscale. Diagnostically determined variables include components of the turbulent energy and stability-dependent mixing coefficients for mean velocity, temperature, and salinity (and biochemical species concentrations when they are added to the list of prognostically calculated variables).

Computationally, the model is fairly economical, and indicates that increased resolution is possible in the future. The model computes the

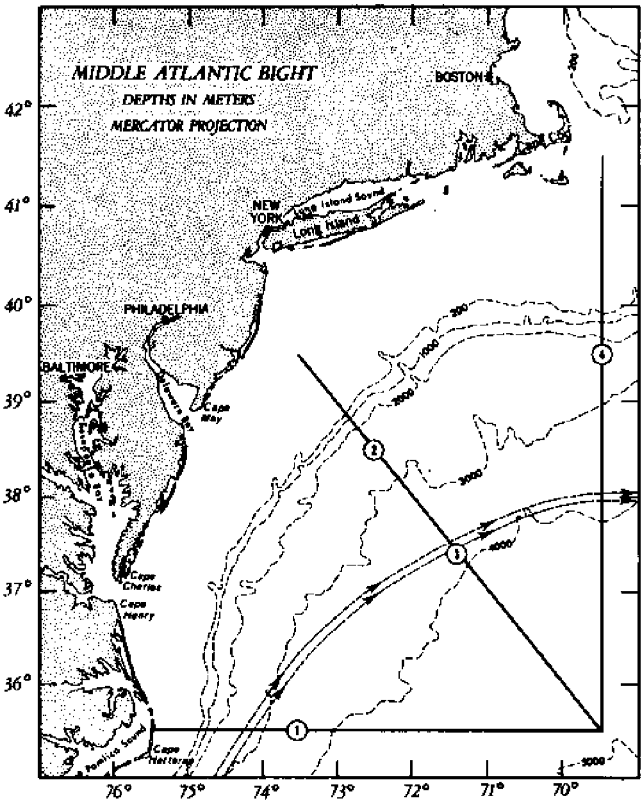

Figure 17. Domain of Blumberg-Mellor Model (see text). Double dashed lines indicate position of Gulf Stream.

vertically averaged velocity and surface elevation fields with a short time increment (about 1 min) required by the shallow water wave speed, and then the full three-dimensional field of variables based on the known surface elevation with a much longer time increment (about 20 min).

The boundary conditions, both numerical and physical, pose major problems. At the open lateral boundaries, temperature and salinity must be prescribed but are used only when inflow occurs. In order to meet these data requirements, transects with station spacing on the scale of the model mesh (1/4°) are required at approximately 2-week intervals. Velocity on the boundaries will be determined by neglecting momentum advection terms in comparison with the Coriolis terms in the equations of motion. The sea surface elevation must be prescribed. The tidal component can probably be determined by measuring the response of coastal sea level observations to variations in boundary elevations. Stipulation of the mean boundary elevation is more of a problem and is tantamount to knowledge of a reference level for absolute geostrophic velocity computation. The specification of sea surface elevation may be greatly aided by sea level data from SEASAT-A. Open boundaries also occur at estuaries where volume flow (river inflow) and temperature are represented by source terms at single horizontal grid locations.

At the sea surface, the model requires wind stress, heat flux or temperature, and water vapor flux. Alternately, using a near surface planetary boundary layer model, 10-m wind velocity, temperature, and water vapor estimates and a radiation flux estimate are required together with surface wave governed estimates of momentum and scalar roughness heights.

The specification of the surface stress represents a critical factor limiting the predictive capability of the model. Theory indicates that detailed prediction of the atmospheric synoptic variations is not possible beyond 2 to 3 weeks.

Final Remarks

We have reviewed a variety of types of oceanographic and atmospheric data that can be used to describe conditions over the northwest Atlantic Ocean. These consist of both archived historical data and operational products that are routinely disseminated and often archived by service organizations. We have emphasized the increasing availability of important data derived from satellite IR and microwave imagery. These data, when used in conjunction with conventional surface-based observations, have resulted in major advances in the description of conditions at the sea surface. Improved descriptions of the low-level meteorological fields are also becoming available through the use of data from a steadily increasing number of meteorological/oceanographic buoys on or near the continental shelf, coupled with the use of fine mesh planetary boundary layer models for data assimilation-forecasting operations.

In terms of circulation modeling, the data requirements vary greatly between the detailed specification of boundary conditions needed for the Blumberg-Mellor model discussed in the preceding section, and simple empirical or statistical models with more limited goals. For the immediate future it seems likely that the major role of dynamic models will be diagnostic rather than predictive, with empirical relationships the primary tool for seasonal and year-to-year prediction.

In our view, the lack of an adequate subsurface oceanographic data base from which to document the mean mass and circulation fields, and from which an adequate statistical description of the time and space spectra of variance can be developed, represents the major obstacle to circulation modeling development. On the climate scale, as well, subsurface data are still inadequate for documentation of year-to-year variations. Perhaps a synthesis of information from the NMFS/MARAD ship of opportunity program, the standard sections in the northern portion of the area, the experimental NMC 17.5°C depth analyses and synoptic analyses of the surface circulation features will provide the beginning of this type of documentation for the western Atlantic Ocean.

Acknowledgments

Information used in this review was generously provided by a large number of people. Particularly helpful were the following:

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NWS, NOAA
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NESS, NOAA
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GFD Program
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We also wish to thank Robert Beardsley, Harry Van Loon, J. Murray Mitchell, Jr., and A. H. Oort for permission to use or adapt figures from their publications.

Appendix A

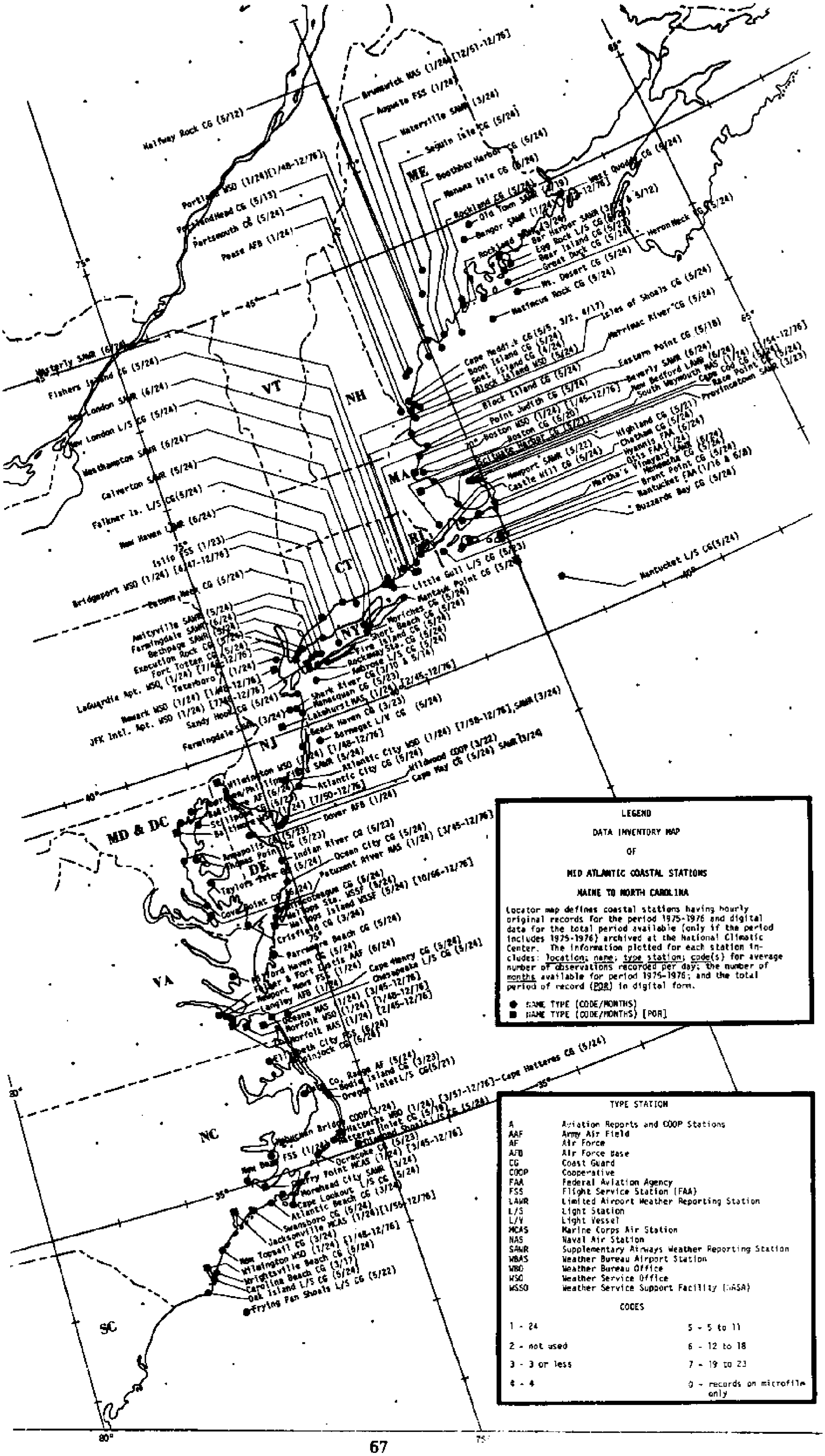
This appendix consists of supplementary material describing the distribution of physical data of various types over the northwest Atlantic and neighboring regions.

The following full-page figures are:

Figure A-1. Inventory map showing periods of available meteorological observations from mid-Atlantic coastal stations (Maine to North Carolina). (Source: NCC)

Figure A-2. Data inventory map of merchant ship surface marine observations (as of 1974) for Atlantic coastal zone (from coast to 500 km seaward). (Source: NCC)

Figure A-3. Data inventory map of surface marine observations (1975-77) and environmental buoy data (as of October 1977) for the Atlantic coastal zone (from coast to 500 km seaward). (Source: NCC)



LEGEND

DATA INVENTORY MAP

OF

MID ATLANTIC COASTAL STATIONS

MAINE TO NORTH CAROLINA

Locator map defines coastal stations having hourly original records for the period 1975-1976 and digital data for the total period available (only if the period includes 1975-1976) archived at the National Climatic Center. The information plotted for each station includes: location; name; type station; code(s) for average number of observations recorded per day; the number of months available for period 1975-1976; and the total period of record (POR) in digital form.

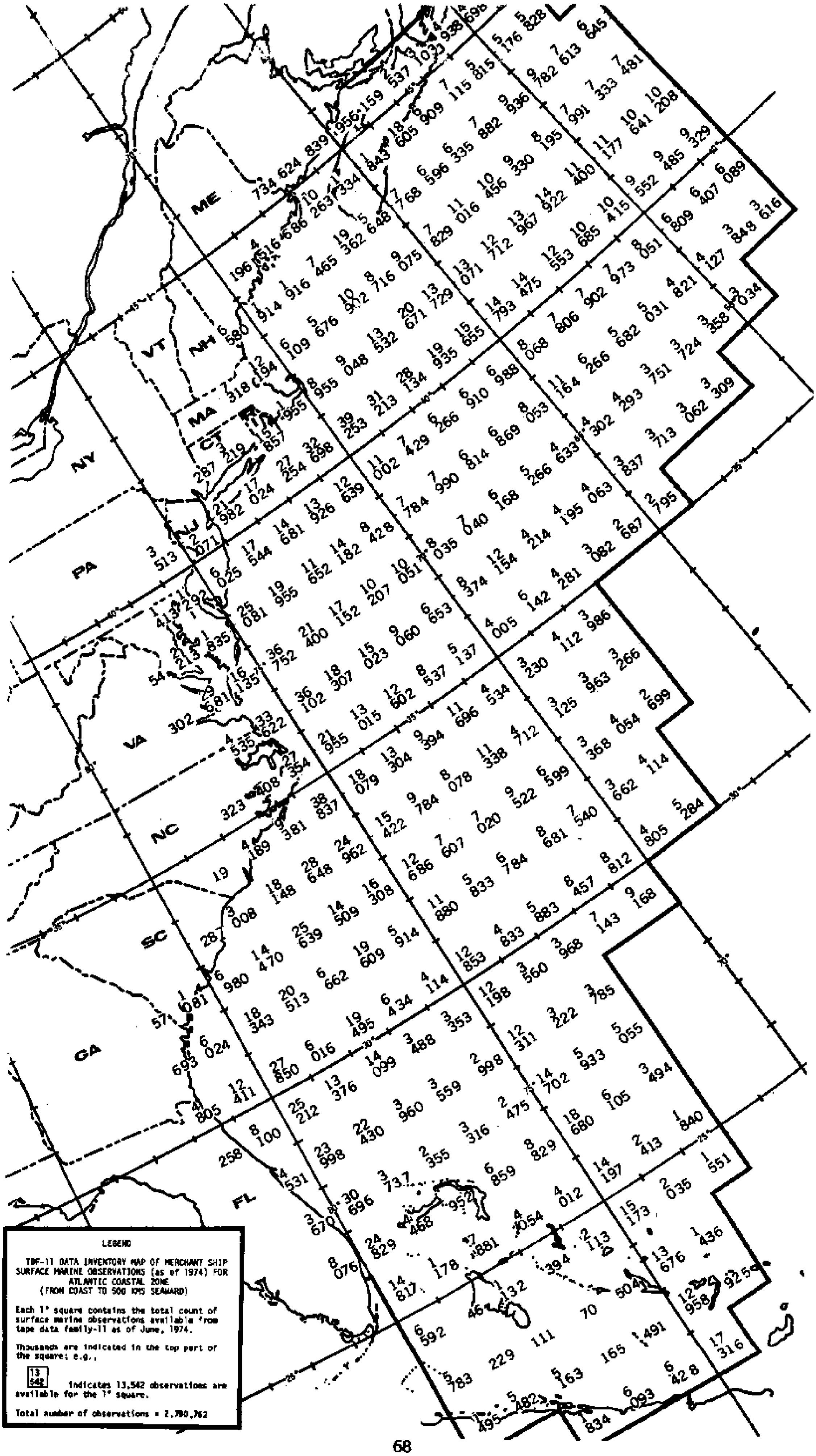
● NAME TYPE (CODE/MONTHS)
■ NAME TYPE (CODE/MONTHS) [POR]

TYPE STATION

A	Aviation Reports and COOP Stations
AAF	Army Air Field
AF	Air Force
AFB	Air Force Base
CG	Coast Guard
COOP	Cooperative
FAA	Federal Aviation Agency
FSS	Flight Service Station (FAA)
LAWR	Limited Airport Weather Reporting Station
L/S	Light Station
L/V	Light Vessel
MCAS	Marine Corps Air Station
NAS	Naval Air Station
SAWR	Supplementary Airways Weather Reporting Station
WBAS	Weather Bureau Airport Station
WBO	Weather Bureau Office
WSO	Weather Service Office
WSSO	Weather Service Support Facility (NASA)

CODES

1 - 24
2 - not used
3 - 3 or less
4 - 4
5 - 5 to 11
6 - 12 to 18
7 - 19 to 23
9 - records on microfilm only



LEGEND

TDF-11 DATA INVENTORY MAP OF MERCHANT SHIP SURFACE MARINE OBSERVATIONS (as of 1974) FOR ATLANTIC COASTAL ZONE
(FROM COAST TO 500 KMS SEAWARD)

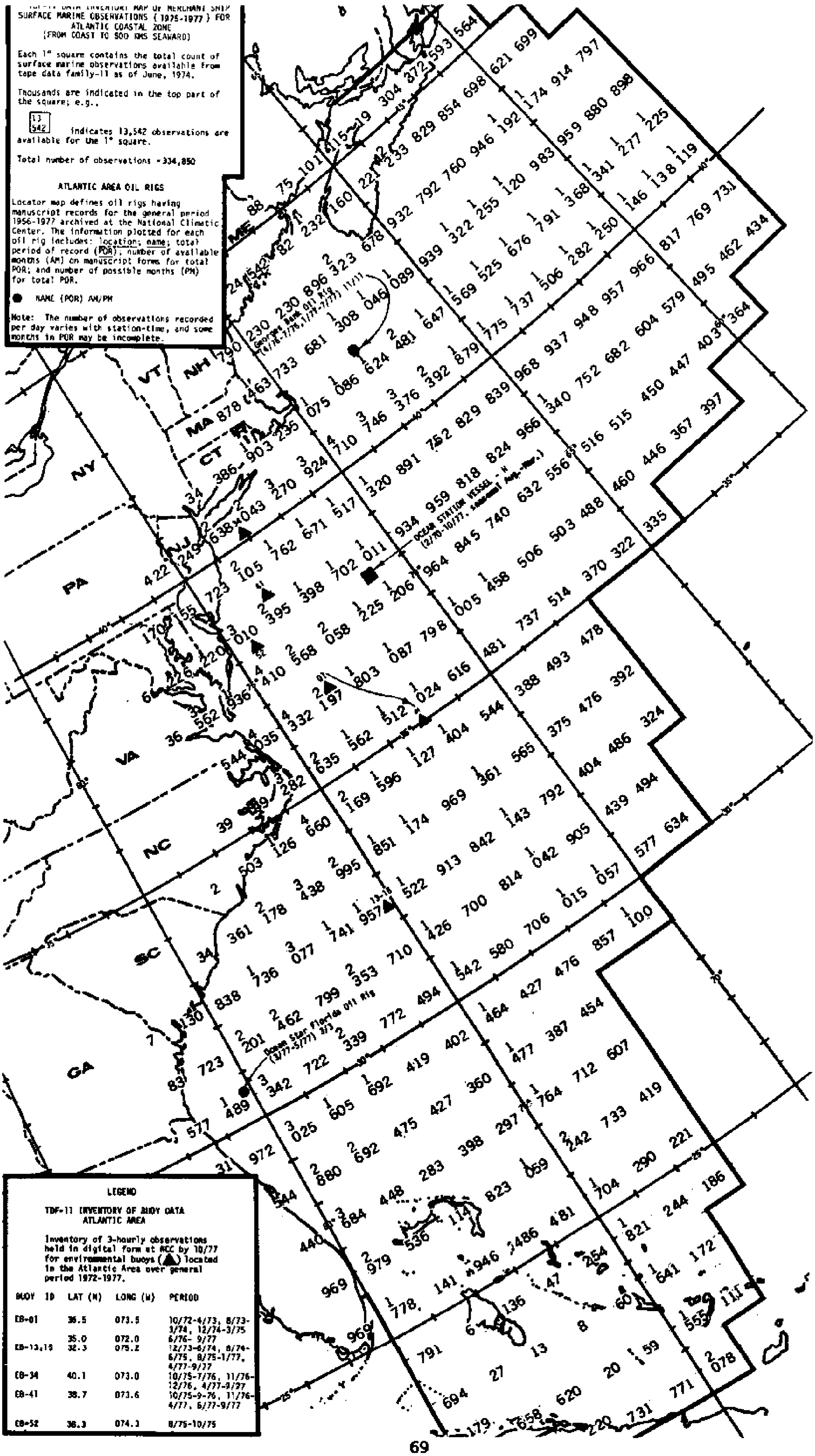
Each 1° square contains the total count of surface marine observations available from tape data family-11 as of June, 1974.

Thousands are indicated in the top part of the square; e.g.,

13
542

indicates 13,542 observations are available for the 1° square.

Total number of observations = 2,790,762



TDF-11 DATA INVENTORY MAP OF MERCHANT SHIP
SURFACE MARINE OBSERVATIONS (1975-1977) FOR
ATLANTIC COASTAL ZONE
(FROM COAST TO 500 KMS SEAWARD)

Each 1° square contains the total count of surface marine observations available from tape data family-11 as of June, 1974.

Thousands are indicated in the top part of the square; e.g.,

13
542

indicates 13,542 observations are available for the 1° square.

Total number of observations =334,850

ATLANTIC AREA OIL RIGS

Locator map defines oil rigs having manuscript records for the general period 1956-1977 archived at the National Climatic Center. The information plotted for each oil rig includes: location; name; total period of record (POR); number of available months (AM) on manuscript forms for total POR; and number of possible months (PM) for total POR.

● NAME (POR) AM/PM

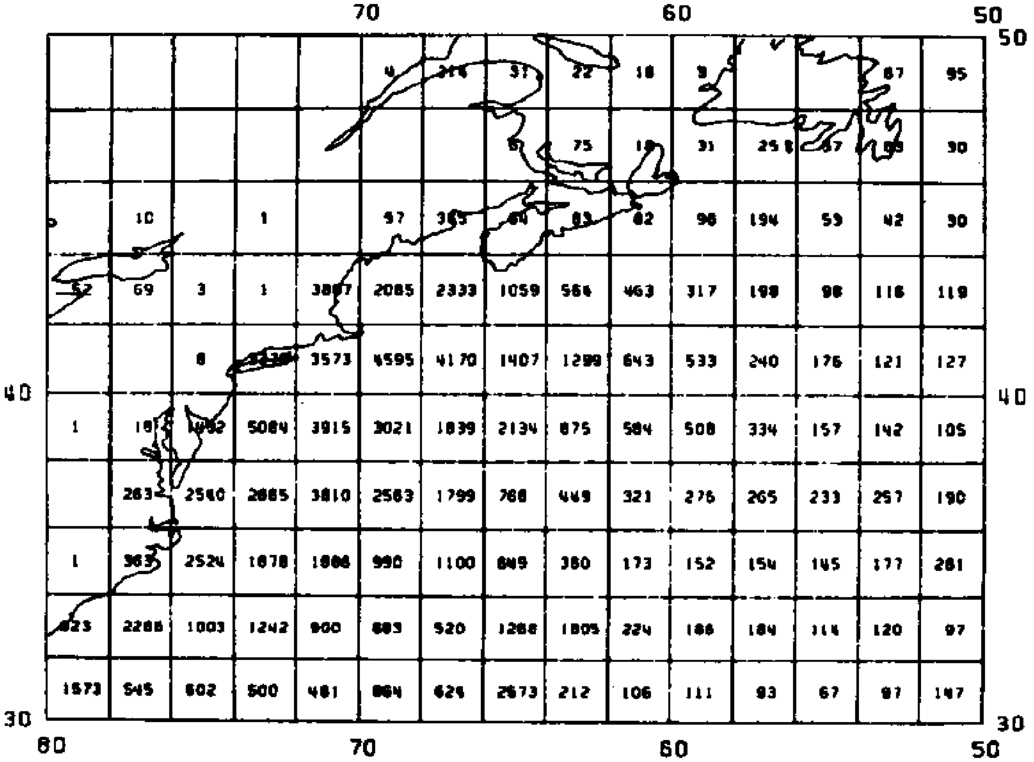
Note: The number of observations recorded per day varies with station-time, and some months in POR may be incomplete.

LEGEND

TDF-11 INVENTORY OF BUOY DATA
ATLANTIC AREA

Inventory of 3-hourly observations held in digital form at NCC by 10/77 for environmental buoys (▲) located in the Atlantic Area over general period 1972-1977.

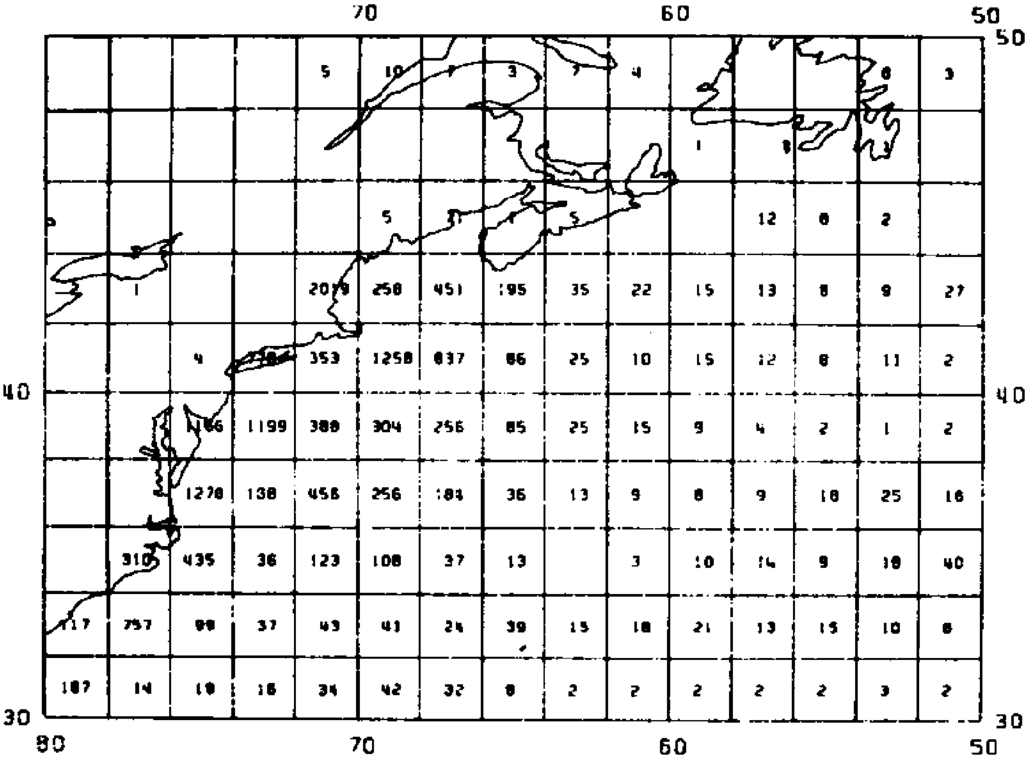
BUOY ID	LAT (N)	LONG (W)	PERIOD
EB-01	38.5	073.5	10/72-4/73, 8/73-3/74, 12/74-3/75
	35.0	072.0	6/76- 9/77
EB-13,15	32.3	075.2	12/73-6/74, 8/74-6/75, 8/75-1/77, 4/77-9/77
EB-34	40.1	073.0	10/75-7/76, 11/76-12/76, 4/77-9/77
EB-41	38.7	073.6	10/75-9-76, 11/76-4/77, 6/77-9/77
EB-52	38.3	074.3	8/75-10/75



Monthly Totals

Jan	5904
Feb	5731
Mar	6043
Apr	8318
May	11085
Jun	12395
Jul	10314
Aug	10446
Sep	7707
Oct	8455
Nov	8518
Dec	5782

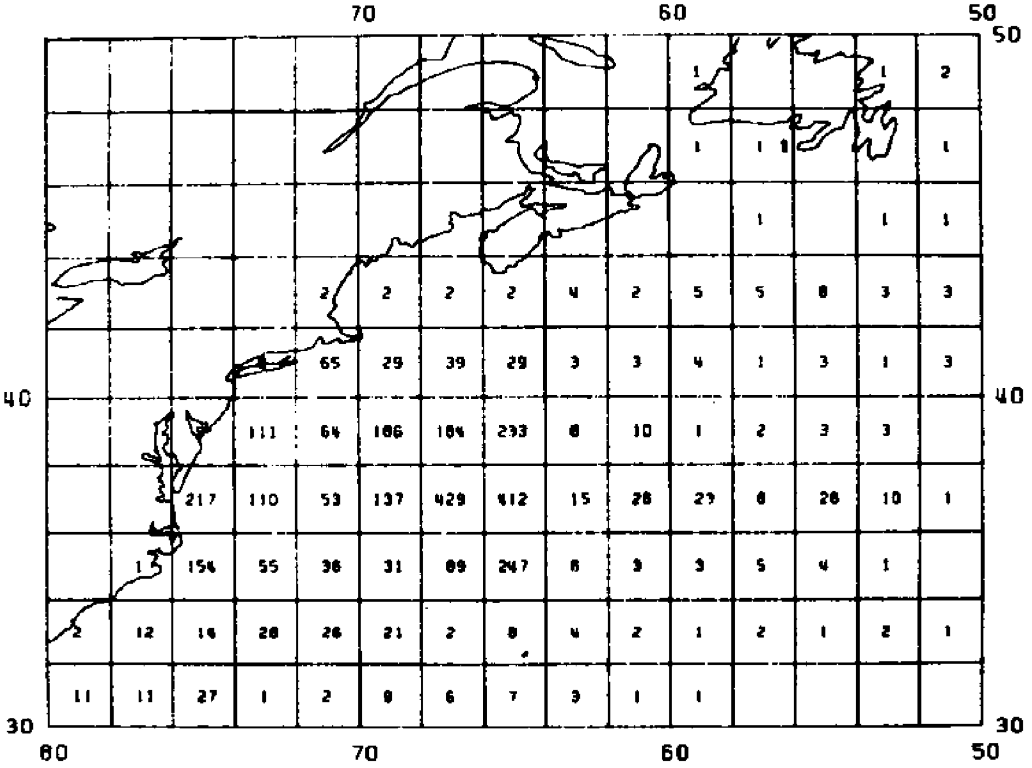
Figure A-4. Counts of MBT data in the NODC archive for the period 1941 to 1967 for 2° squares over the northwest Atlantic. (Source: NODC)



Monthly Totals

Jan	696
Feb	649
Mar	1546
Apr	1403
May	1608
Jun	1554
Jul	1810
Aug	1249
Sep	1450
Oct	1469
Nov	1232
Dec	647

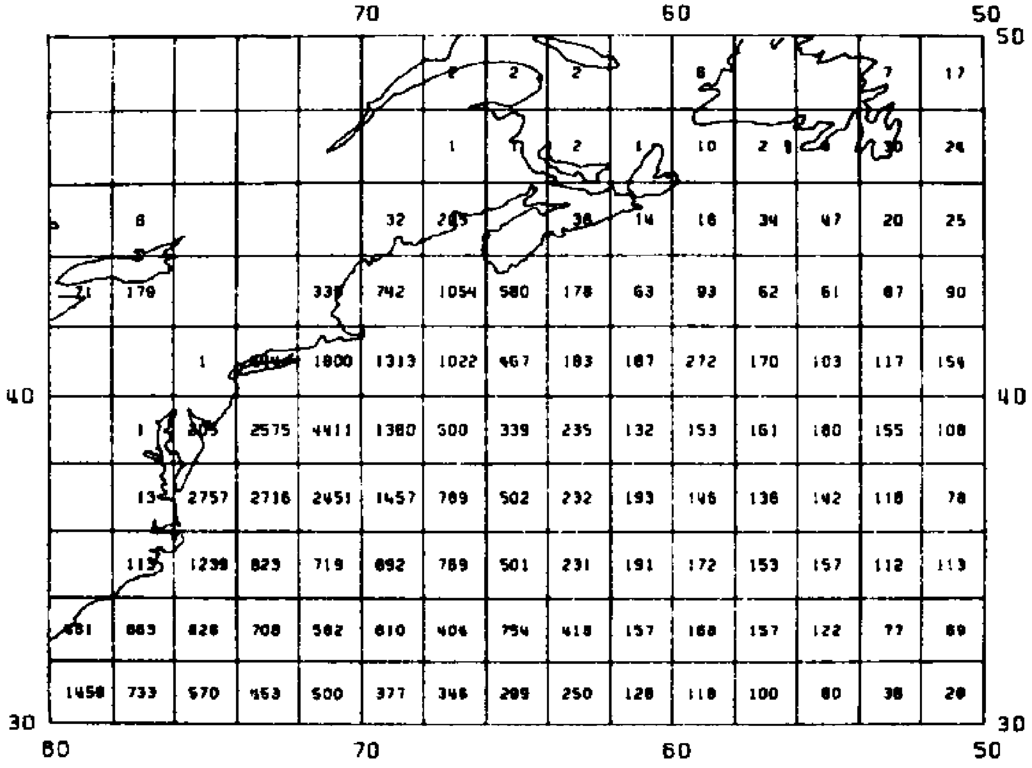
Figure A-5. Same as above except for the period 1968 to 1977. (Source: NODC)



Monthly Totals

Jan	25
Feb	31
Mar	147
Apr	49
May	281
Jun	436
Jul	397
Aug	256
Sep	338
Oct	738
Nov	550
Dec	109

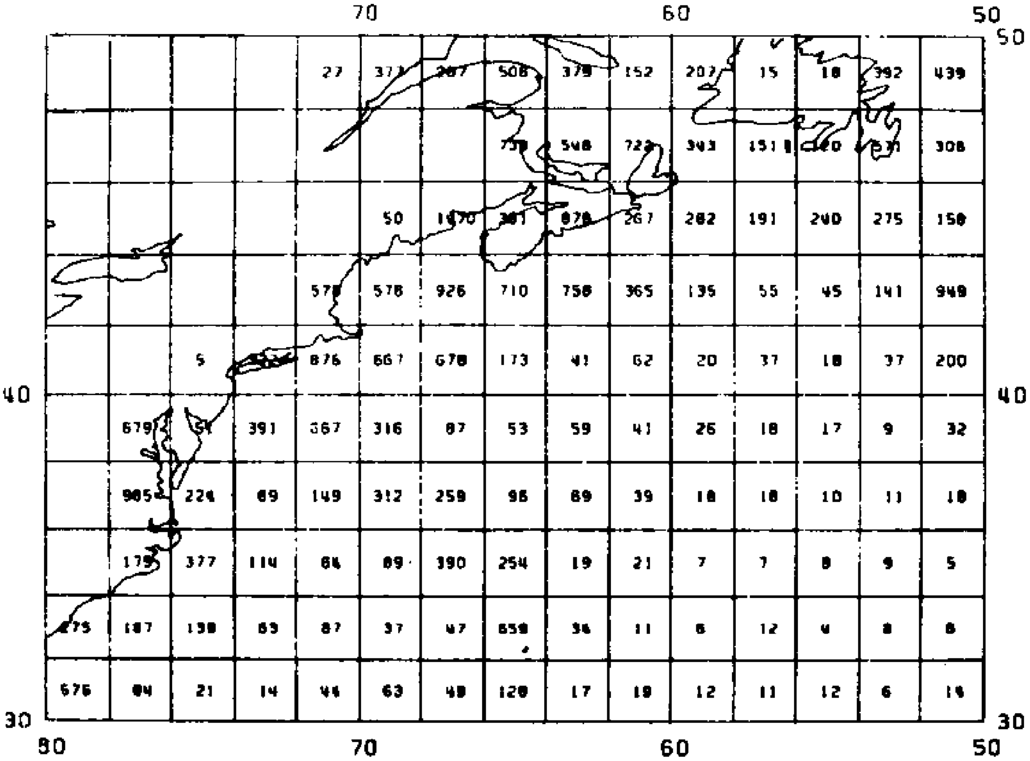
Figure A-6. Counts of XBT data in the NODC archive from 1962 to 1967 for 2° squares over the northwest Atlantic. (Source: NODC)



Monthly Totals

Jan	2835
Feb	2753
Mar	4916
Apr	4964
May	5966
Jun	3324
Jul	3140
Aug	3710
Sep	5270
Oct	4878
Nov	4913
Dec	3933

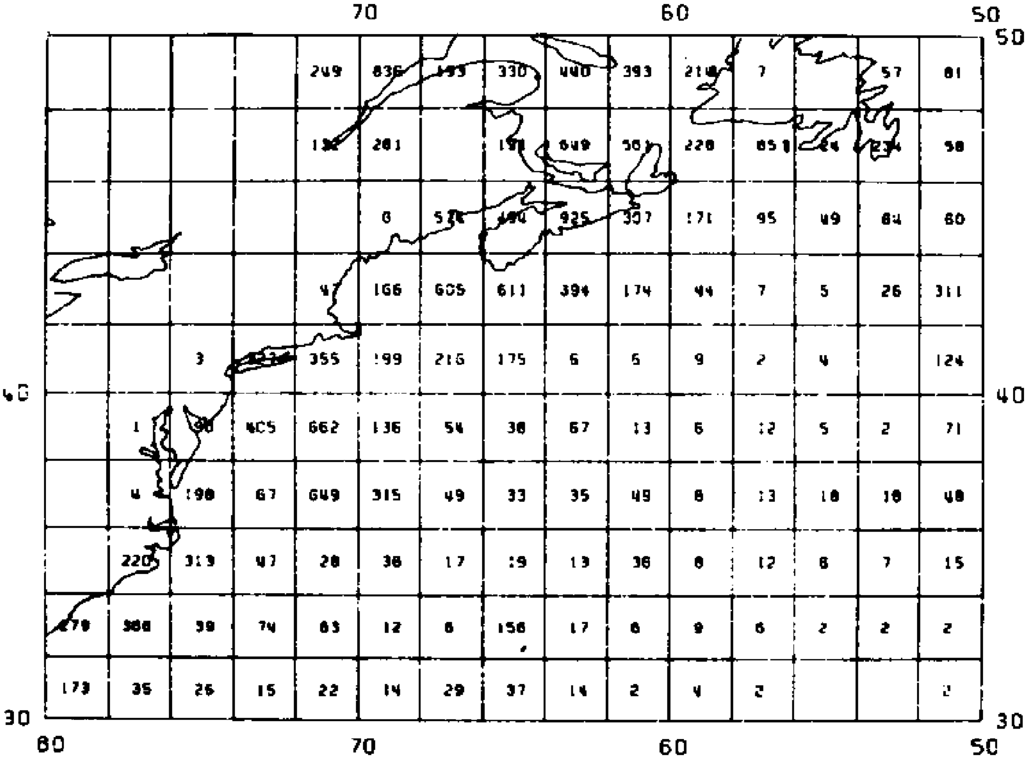
Figure A-7. Same as above except for the period 1968 to 1977. (Source: NODC)



Monthly Totals

Jan	871
Feb	1098
Mar	1823
Apr	2528
May	2884
Jun	3689
Jul	3525
Aug	4476
Sep	2482
Oct	1871
Nov	1467
Dec	1040

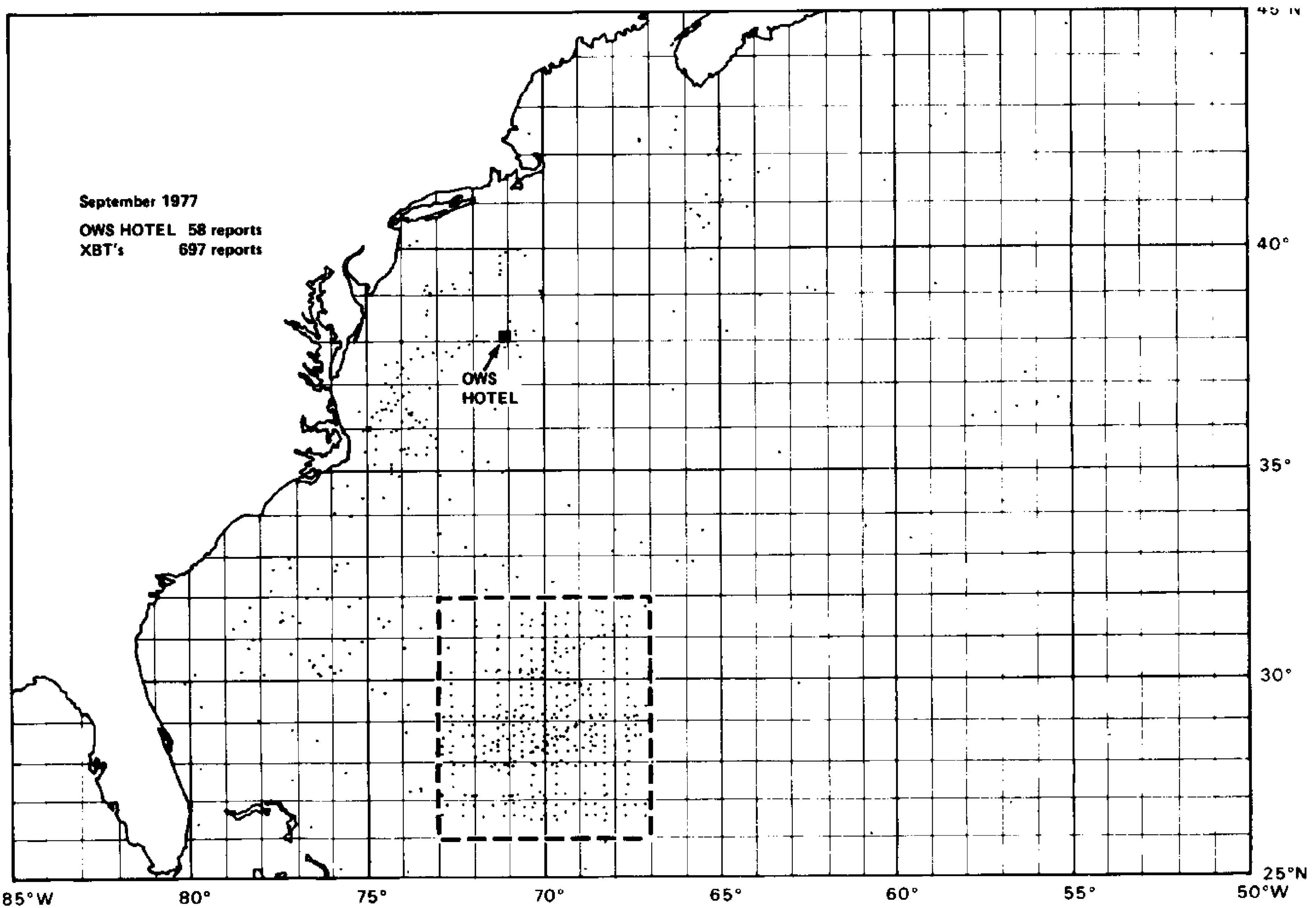
Figure A-8. Counts of station data in the NODC archive for the period 1900 to 1967 for 2° squares over the northwest Atlantic. (Source: NODC)



Monthly Totals

Jan	982
Feb	1137
Mar	1029
Apr	994
May	1710
Jun	1839
Jul	2501
Aug	2661
Sep	1733
Oct	1097
Nov	1037
Dec	343

Figure A-9. Same as above except for the period 1968 to 1977. (Source: NODC)



Locations are shown for all bathythermograph (BT) reports received at the National Meteorological Center in Washington, D. C. for the month of September. Ocean Weather Station (OWS) HOTEL sent 58 subsurface temperature reports. The data density within the dashed line is due to the POLYMODE experiment, a joint US-USSR study to determine the role of mesoscale eddies in the dynamics of large-scale general ocean circulation.

Figure A-10. Distribution of bathythermograph data received at NMC for September 1977. From Gulf Stream, 1977: III(9), p. 3. (Source, NMC)

Figure A-11. NMC Oceanographic Data Summary
1976-1977

Summary of worldwide BATHY, TESAC, and buoy data transmitted to NMC through operational channels from 1976 to 1977 (Source: NMC).

Month	*Total Obs.*		*BATHYs*		*TESACs*		*BUOYs*	
	1976	1977	1976	1977	1976	1977	1976	1977
January	2777	2829	1957	2256	189	80	631	493
February	2946	2836	2415	2281	88	116	443	439
March	2833	2874	2234	2469	284	158	315	247
April	2685	3220	1839	2188	620	663	226	369
May	2808	3112	2189	2333	378	299	241	480
June	3710	3309	2432	2378	856	477	422	454
July	3006	3641	2232	2971	167	225	607	445
August	3262	4197	2211	3316	174	400	877	481
September	3567	4111	2270	3332	110	174	1187	605
October	4095	3807	2680	2894	63	200	1352	713
November	2791	3956	2047	2684	101	413	643	859
December	2791	3497	1984	2450	90	143	717	904
TOTALS								
ALL DATA	37,271	41,399	26,490	31,552	3,120	3,358	7,661	6,489
IGOSS	26,602	30,438	16,024	20,729	2,917	3,220	7,661	6,489

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Nature and Adequacy of Biological Data Bases: Plankton

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Introduction

A major objective of biological oceanography is to quantify the processes regulating food web structure and dynamics. This would allow the construction of appropriate models. In the context of the Climate and Fisheries Workshop, a desirable model would be one which relates the regulation of fishery dynamics to interacting biotic and physical factors. Such models differ from and would supplement those presently used to reach fishery management or sustainable yield decisions. They would emphasize the time-dependent coupling of the different trophic levels and the influence of the physical field on such coupling. Ideally, for example, this would allow *quantitative* modeling of the linkage (and prediction) between wind intensity and herbivorous fish yields in upwelling areas.

Unfortunately, fishery biologists and plankton biologists have tended to work independently of each other. Fishery biologists have tended to ignore lower trophic levels, which they usually treat only cursorily. Thus, chlorophyll is usually the measure of phytoplankton abundance used, and displacement or settling volume the measurement of zooplankton abundance. These static observations are usually valueless. Plankton biologists emphasize phytoplankton/zooplankton relationships, and have essentially ignored higher trophic level dynamics such as grazing and nutrient excretion impacts on plankton dynamics. Thus, the common view that plankton studies have contributed minimally to our knowledge of fisheries dynamics, and *vice versa,* is not surprising. There has been virtually little effort in the United States to carry out appropriate studies with the total food web in mind.

In the following synopsis I will outline some aspects of plankton biology which may be helpful toward bridging this artificial gap between plankton and fishery biologists. Hopefully, it will also encourage much needed coherent field and laboratory studies to clarify how primary production passes up the food web to support fisheries. Or, as a fishery biologist might prefer to view it, how a given fishery is regulated by lower trophic levels.

Some Characteristics of Plankton Dynamics

Seasonal Cycles

The intensity of phytoplankton production varies seasonally, in addition to regional differences in total annual production. This seasonal variation is reflected in a series of abundance pulses over an annual cycle. Figure 1 illustrates that one or two major phytoplankton blooms are characteristic of representative regions. When viewed on a global scale, three general patterns are evident (Figure 2). Arctic waters are characterized by a single annual pulse. Temperate waters are generally two-pulsed systems, and in tropical waters a dampened cycle of modest population oscillations occurs. In enriched nearshore waters the annual bloom pattern consists of a series of blooms of irregular duration and magnitude rather than exhibiting the one- or two-pulsed trends depicted in Figures 1 and 2.

The significance of these bloom patterns is that a continuous, even production and flow of

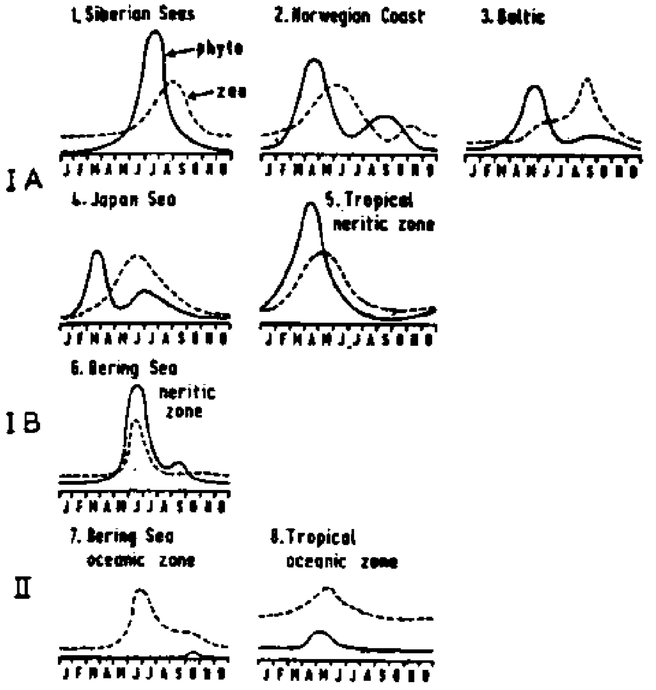

Figure 1. The seasonal cycles of plankton communities (Heinrich, 1962).

phytoplankton carbon is not available to the food web. During the major blooms a large amount of excess carbon may be produced over that grazed. This surplus is degraded microbially within the water column or on the sea floor. Moreover, the representative trends in Figures 1 and 2 suggest that low phytoplankton standing stock levels occur during much of the annual cycle.

These characteristics suggest the need for synchronization between herbivore occurrence and production and the regionally characteristic phytoplankton bloom dynamics. With regard to the zooplankton, two types of phasing are apparent (Figures 1 and 2). Zooplankton pulses are either asynchronous with the phytoplankton pulses or they occur simultaneously. The cycles are stated to be *unbalanced* when the phytoplankton pulse precedes the zooplankton pulse and *balanced* where the pulses are coincident. In an unbalanced cycle, phytoplankton biomass usually exceeds zooplankton biomass. Unbalanced systems are generally characteristic of polar and temperate waters and upwelling regions. Balanced systems usually occur in oligotrophic, warm seas. The primary factors of the unbalanced cycles are the extraordinarily rapid phytoplankton growth coupled with the temperature-regulated delay in zooplankton growth and reproduction during the major bloom. This temperature-regulated delay in zooplankton recruitment becomes progressively diminished, with increasing temperature resulting in the balance of cycles in tropical waters. The significance of this characteristic to food web dynamics is that temperature modifies and regulates trophic transfer of phytoplankton carbon. In cycles markedly unbalanced, a considerable amount of phytoplankton carbon may not be available to "desirable" species (herbivores) and degraded by microbial processes. In balanced cycles, a closer coupling between trophic levels occurs, with herbivores being able to take quick advantage of increases in primary production.

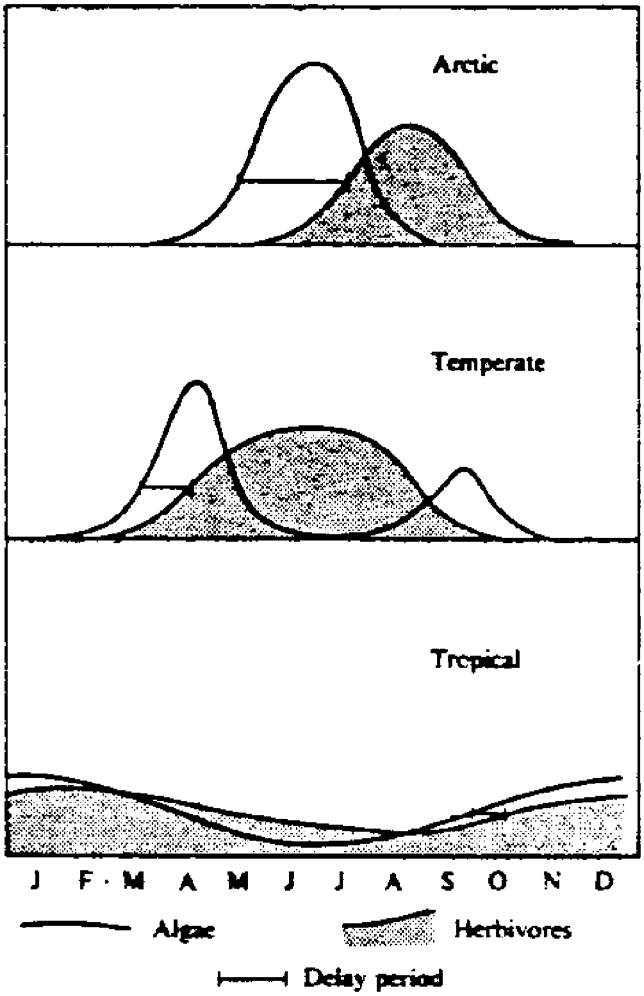

Figure 2. Diagrammatic representation of plankton production cycles in different regions (Cushing, 1959).

A phytoplankton pulse consists of two major elements: bloom inception and bloom termination. The inception of the major annual bloom is usually triggered either by a reduction in vertical mixing (increases the residence time of the phytoplankton within the euphotic zone) or by nutrient enrichment. Our knowledge is sufficient to allow the building of bloom inception models based on time-dependent physical models in well-mixed, i.e., winter, conditions on the continental shelf, as well as simple one-dimensional models of low-frequency systems such as the central gyres. However, we cannot as yet build satisfactory physical models of stratified conditions to handle seasonal thermocline development, wind mixing, and nutrient cycling.

A corollary of this is the present great difficulty in establishing and modeling the causes of the major bloom termination, which usually occurs during stratified summer conditions (Figures 1 and 2). The observed phytoplankton decline accompanies a reduction in ambient nutrient levels and an increased zooplankton biomass. Zooplankton function in two major processes during this period: as they *graze* down the phytoplankton, they simultaneously *excrete essential nutrients* required for continued phytoplankton growth. Presently, we lack sufficient data on the grazing terms and rates of nutrient excretion for key zooplankton species. Secondary production estimates based on cohort analysis of field populations are virtually nonexistent. A complicating factor is the degree to which pelagic processes are coupled to benthic activities. Water column depth influences zooplankton abundance and the extent to which pelagic processes are influenced by benthic processes. The benthic community likewise influences water column dynamics through nutrient excretion and grazing on phytoplankton. Figure 3 illustrates that shallow waters support a lower average standing stock of zooplankton than do deeper waters; biomass increases with depth to about 200 m. It is not possible to define precisely the depth at which pelagic processes become uncoupled from benthic influences, but it is evident that there is an onshore-offshore gradient in the relative contributions of the zooplankton and benthos. Benthic activities can be expected to predominate in shallow waters, with the contribution by zooplankton progressively increasing with water column depth. At depths > 100 m zooplankton probably become preeminent and pelagic processes more or less uncoupled from benthic influence (grazing and nutrient excretion). Our knowledge of these benthic processes is likewise minimal.

We can summarize our present abilities to quantify bloom termination dynamics as follows: Biological dynamic models require data sets, presently unavailable, for specification of the values of coefficients, parameters, initial and boundary conditions. Another constraint is the lack of data on zooplankton cohort production or invertebrate predator dynamics. We thus cannot build dynamic models of more than two to three weeks' time because there is inadequate zooplankton and invertebrate predator data to enable us to extend the calculations past the life cycle of these organisms.

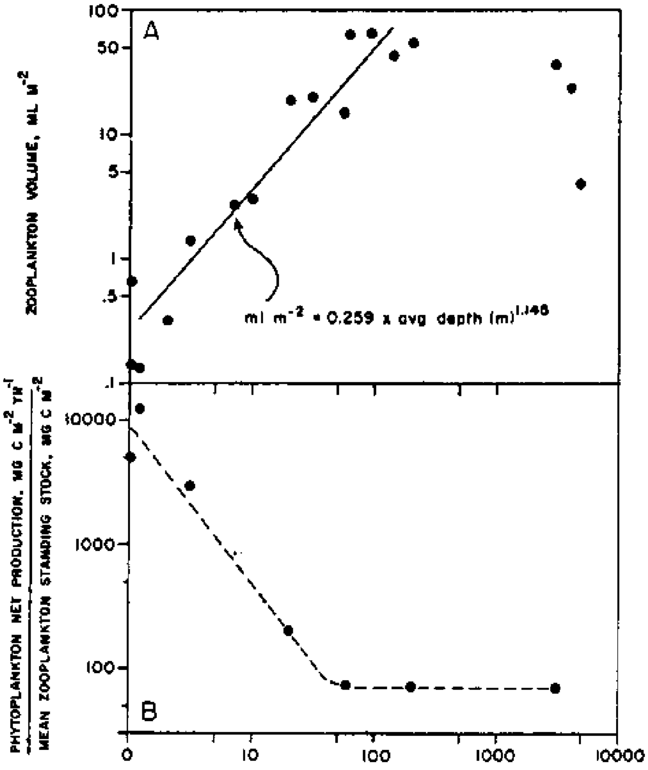

Figure 3. (A) Relationship between average zooplankton standing crop and average depth of the water column sampled in various areas. (B) Ratio of annual net phytoplankton carbon production to the average zooplankton carbon standing stock compared to the average water column depth in various areas (Smayda, 1976).

With regard to modeling of overall dynamics up through the food web, our present capabilities are extremely limited. We do not understand the time-dependent coupling of phytoplankton, zooplankton, larval fish, and invertebrate predators. This sets the time and space limits of present models. With our ability to run phytoplankton models for days and adult fish models for years, the interface data on time scales of months to couple these two types of models are missing (Walsh, personal communication).

Variability in Plankton Cycles

Significant interannual variations in plankton cycles occur where observations have been made over a suitable time period. In Narragansett Bay phytoplankton observations have been made on a weekly basis since 1960 (Figure 4). Here, the annual maximum abundance during the winter-spring bloom varied tenfold from 4500 cells ml^{-1} (1970) to 42000 cells ml^{-1} (1963). Time of inception of the winter-spring maximum has varied from December to April. In 4 years, 1970, 1973 to 1975, the annual maximum occurred during August! Maximum abundance during the summer has varied about ninefold, from 7000 cells ml^{-1} (1967) to 59000 cells ml^{-1} (1975). The causes of these significant seasonal shifts in peak abundance and year-to-year variations in inception and magnitude of the winter-spring bloom in the unpolluted waters of lower Narragansett Bay are unknown.

Similar variability has been reported from the North Sea in time of inception of the spring bloom, zooplankton biomass, and numerical abundance and length of the zooplankton growing season (Figure 5).

There is also considerable variability in the predominance of different plankton groups. Figure 6 (Glover, 1961) illustrates the variations in various zooplankton components occurring over a 10-year period on the northern North Sea herring fishing grounds. Three major periods in zooplankton reorganization are recognizable. From 1949 to 1951, North Sea neritic forms were abundant, which then declined, and more oceanic representatives increased in numbers from 1952 to 1954 and in 1956. During 1957 and 1958 an overall decrease in zooplankton abundance occurred; species showing a distributional pattern intermediate between the North Sea types and the oceanic representative then predominated. A striking example of another type of variability is evident in the dynamics of the copepod ***Pseudocalanus elongatus*** over a 25-year period in the North Sea (Figure 7). A systematic long-term trend, superimposed on the annual cycle in which the overall annual abundance between 1948 and 1968 has progressively decreased, characterizes this species. This decrease has also been accompanied by a progressively shorter "biological season" (Glover et al., 1974). The copepod ***Temora longicornis*** reveals a different long-term trend. Although the length of its growing season has remained constant, it has shifted with time, becoming progressively later from 1948 to 1966.

These limited long-term observations clearly establish the significant variability characterizing plankton communities. This variability characterizes both phytoplankton and zooplankton. And it is manifested in species composition, abundance, and time of duration and magnitude of abundance for the total population and individual species. Cause-and-effect relationships cannot be estab-

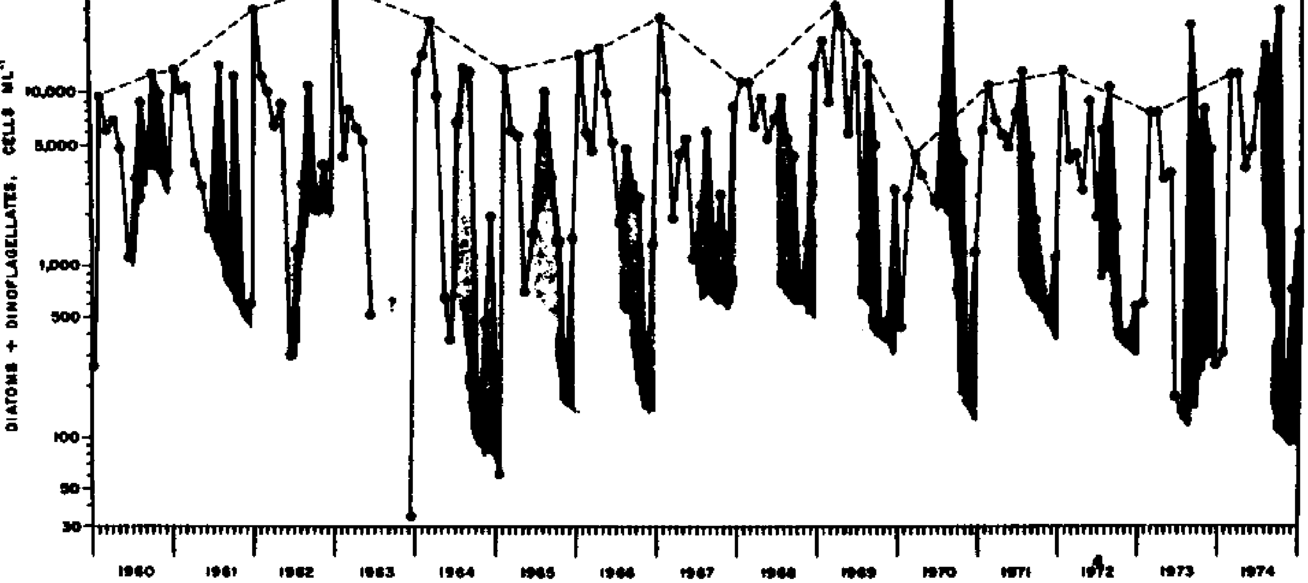

Figure 4. Maximum monthly abundance of the diatom and dinoflagellate populations in the surface waters of lower Narragansett Bay from 1960 through 1974 (Smayda, 1976).

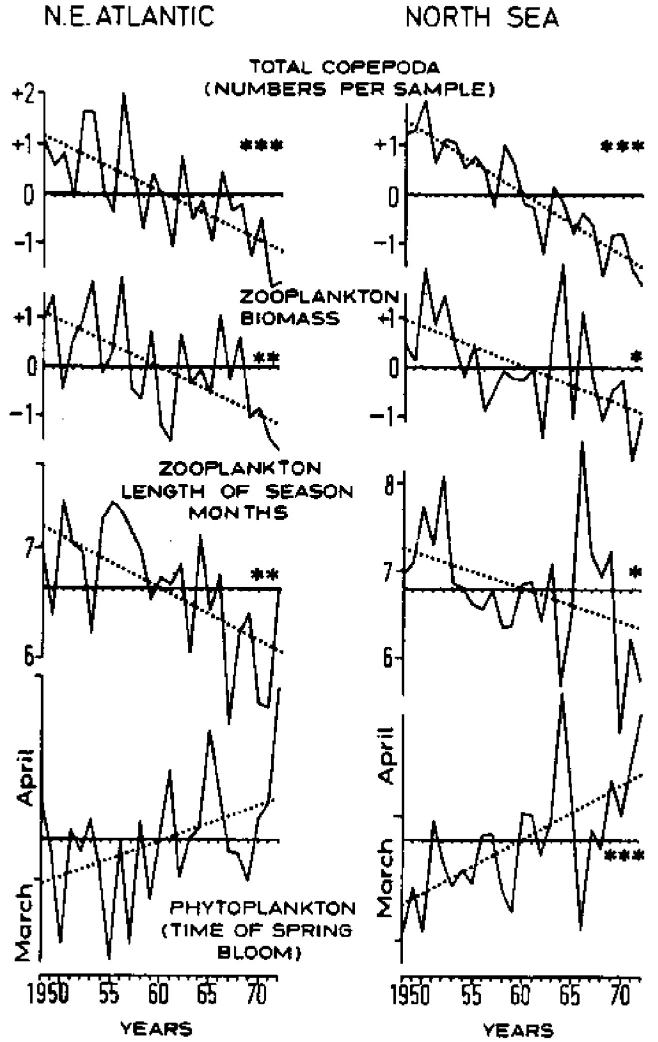

Figure 5. Fluctuations in the plankton in a region of the northeast Atlantic and the North Sea. The results in the upper two pairs of graphs are given as standard deviation units. In the lower two pairs the ordinate values are plotted about the mean values; for calculated trend lines, * = significant at P = < 5%, ** < 1% and *** < 0.1% (Glover et al., 1974).

lished because requisite data have not been simultaneously recorded. Neither can the effects of both short- and long-term climatological events, nor of teleconnections, on this variability be established. With respect to the fisheries, such variability at these lower trophic levels clearly can be expected to influence fish species dynamics in some way. Changes in the occurrence and abundance of desirable food species, asynchronous occurrences of essential grazer-prey taxa, and other subtle consequences would appear to significantly impact food web dynamics.

A prime contemporary need is to further document such long-term variability; to attempt to

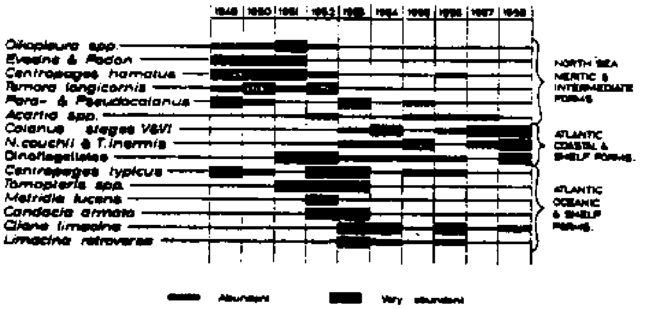

Figure 6. The relative seasonal abundance of the plankton of the northern North Sea herring fishing grounds based on Plankton Indicator samples (Glover, 1961).

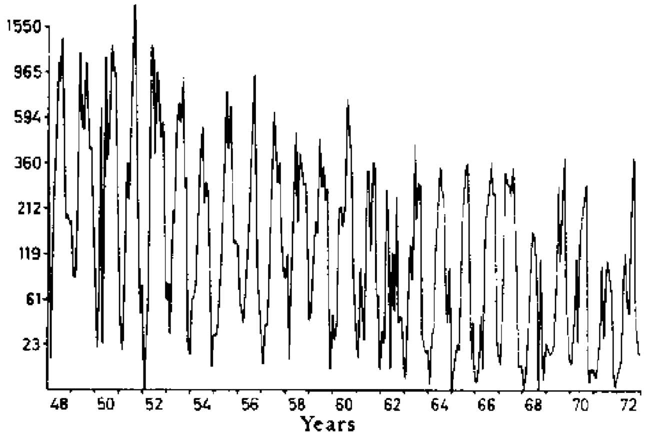

Figure 7. Abundance of the copepod *Pseudocalanus elongatus* (as average numbers per sample) at monthly intervals from 1948 through 1972 in the east-central North Sea (Glover et al., 1974).

quantify the mechanisms of variability in marine populations and to carry out basic experimental studies with key species. Obviously, we cannot monitor or experiment with all species, follow their abundance, fecundity, survival, seasonal occurrences, and, in the case of fishes, their distribution. Nor can we monitor and experiment with all relevant environmental factors known to influence organisms. Fishery biologists, plankton biologists, physical oceanographers, and meteorologists should begin to discuss, and then implement, the types of coherent interdisciplinary studies that are needed and are currently practical to overcome our present inability to do little more than to speculate about the causes and consequences of variability in marine populations.

Species Succession

A basic characteristic of marine communities is the seasonal succession in species (Figure 8). Traditionally, such changes have been treated unrealistically as taxonomic phenomena. For this reason, phytoplankton and zooplankton communities have often been reduced to a common property, such as chlorophyll, carbon, or displacement volume as a measure of abundance. In the case of phytoplankton, measurement of primary production has often been the sole measure of phytoplankton availability. However, even a modest awareness of the natural behavior and physiology of phytoplankton and zooplankton reveals that significant interspecific differences occur in their physiology, behavior, and suitability as prey. Thus, in a species succession (Figure 8) the changes in taxa are secondary to the dynamic aspects and food web consequences associated with such successions.

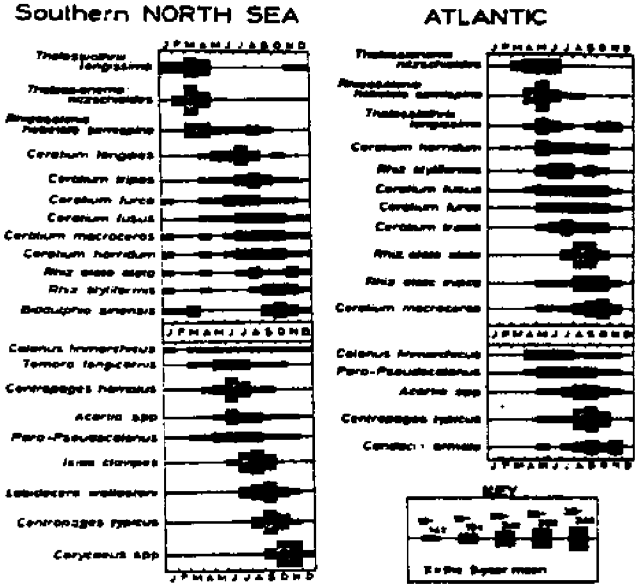

Figure 8. The average abundance of the common species of phytoplankton and copepods in the southern North Sea and over the deep Atlantic part of the Continuous Plankton Recorder Survey region (Glover, 1961).

It is essential, therefore, that the species composition and abundance be routinely established in field studies, including those concerned with fisheries problems. With regard to the phytoplankton, species succession has two interrelated aspects. The species composition influences community structure, and the cell sizes characteristic of the species composition affect community function and trophic interrelationships. In turn, the food "quality" of the phytoplankton species differs interspecifically, and the food value of a given phytoplankton species to a grazer differs between grazer.

The classic example of an unacceptable phytoplankton species as a food source is *Phaeocystis pouchetii*. This large, gelatinous colonial species blooms extensively during the winter-spring in temperate and polar waters. During these blooms, zooplankton and herring avoid *Phaeocystis* patches. This avoidance is thought to be related to inimical substances released into the water column by *Phaeocystis*.

The well-publicized anoxia in the New York Bight during the summer of 1976 was accompanied by an unusual and prodigious bloom of the dinoflagellate *Ceratium tripos*. While the exact conditions triggering this outbreak are unresolved, one view has contended that the oxygen deficiency resulted from degradation of the ungrazed *Ceratium* population. Because of its large size, *Ceratium tripos* may have been ungrazed, which, combined with minimal advective losses and steady recruitment, led to its remarkable population explosion. Extensive shellfish and finfish mortality accompanied this anoxic event. If indeed this event resulted from an ungrazed phytoplankter, then this episode might have been circumvented if some other more suitable phytoplankton species developed during the summer of 1976. This uncertainty illustrates our substantial inability to account for single species dynamics, such as *Phaeocystis* or *Ceratium* blooms. There is a growing need to understand single species dynamics at all trophic levels.

There is additional evidence for the need to know the species composition and size characteristics of natural communities. Bivalve larvae, copepods, barnacle larvae are now well known to have very specific food requirements not provided by all species of phytoplankton. Thus, certain species of barnacle larvae will reproduce and metamorphose only when diatoms are provided as a food source; other species require microflagellates exclusively. The pioneering experiments of Lasker and coworkers (see Lasker and Zweifel, 1978) have shown the great importance of phytoplankton species composition and cell size to first-feeding northern anchovy larvae. Durbin and Durbin (1975) have likewise shown that the grazing rates of the Atlantic menhaden *Brevoortia tyrannus* are a function of particle size and concentration.

Grazers show significant selectivity in their food preferences, even members of the same genus. Figure 9 illustrates this, based on a study of 16 species of tropical euphausiids. Moreover, the food preferences of a maturing predator change with increasing size, or during different stages of growth. Figure 10 illustrates this phenomenon based on a study of the chaetognath *Parasagitta elegans*.

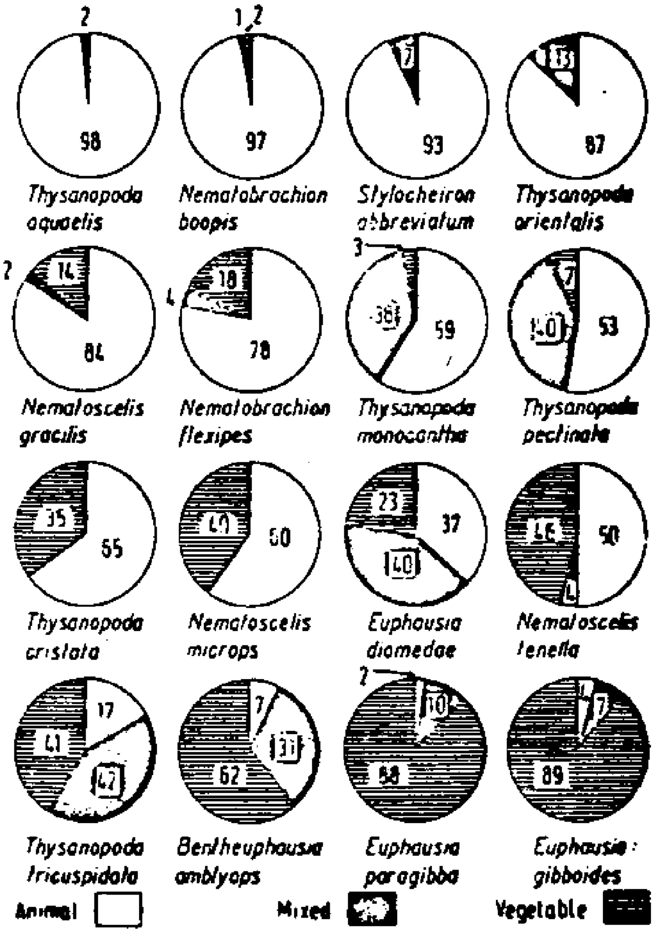

Figure 9. Relative quantities of phytoplankton and zooplankton eaten by species of tropical euphausiids (Wyatt, 1976).

This diverse evidence strongly suggests the importance of establishing the food preferences of predators over their developmental cycle, the species composition, abundance and organism size structure in natural communities, and the *in situ* dynamics of such key species. Our knowledge of such processes is very skimpy. Yet the evidence suggests that our eventual ability to quantify, model, and predict food web dynamics up through the fisheries will require such understanding. Which organisms are present, in what concentrations, and at what time over the annual cycle are aspects of food web dynamics no less important than total production or efficiency of energy transfer. Lasker's work surely illustrates the value of the type of approach needed if fishery biologists and plankton biologists are to achieve their common research objective: to understand marine food webs.

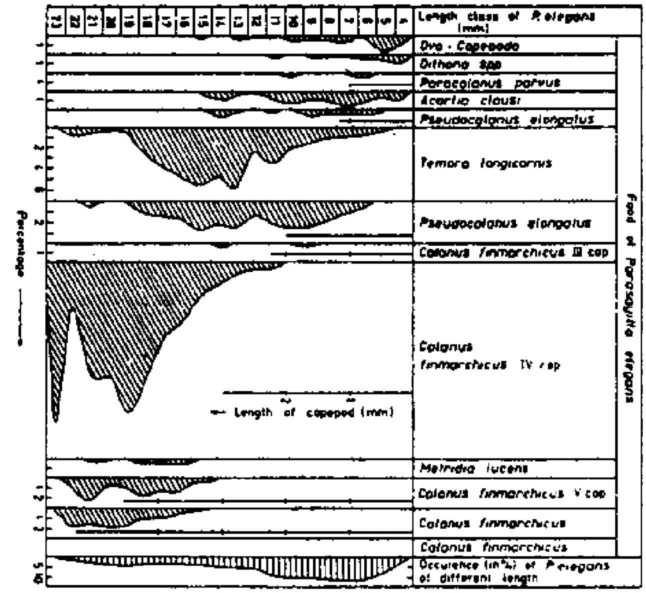

Figure 10. Percentage composition of food of the chaetognath *Parasagitta elegans* in relation to predator size (Wyatt, 1976).

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Some Remarks on the Nature of the Fisheries Data Base in the Northwest Atlantic

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Introduction

The principal purpose of this talk is to give a brief outline of the nature of available data that might be used to identify causal relationships between fish production and climatic factors. To achieve true predictive capability, it is necessary that controlling mechanisms be identified — statistical correlations by themselves rarely lead to accurate predictive models. The single most important life process that governs changes in fish production is the recruitment process, which involves maturation, fecundity, spawning, and growth and survival through the egg-larval-juvenile stages. There is strong evidence that the major factors controlling success of year classes for most fish populations operate during the larval stages. Understanding the physical and biological events that control the timing and distribution of egg and larval stages of most species, and their food supply, predators, and subsequent survival, will probably require a multifaceted research program that involves coordinated physical and biological studies over a rather wide range of events in time and space. In short, it will require an ecosystem-oriented program that takes account of multispecies interactions as well as atmospheric and oceanic events.

The Northeast Fisheries Center since its formation in 1972 has been developing such an approach for the continental shelf region from Cape Hatteras to Nova Scotia. Needless to say, we have a long way to go before an adequate time series of data on early life stages of most major species becomes available. However, a good beginning has been made, and in the next five to ten years it is anticipated that a number of key hypotheses about the factors controlling reproductive success and other biotic-abiotic interactions may be tested.

The fishery and related ecosystem data base is classified into four categories: (1) harvest statistics, (2) monitoring biomass components of the ecosystem, (3) estimating production of biota, and (4) process-oriented studies. Each of the four categories provides essential information for development of a marine ecosystem model, and they are arranged in order of increasing complexity in the understanding of factors controlling fish production. After a description of the significance and status of each category, a summary chart will be presented that illustrates the state of knowledge in a very general way.

Harvest Statistics

Complete and accurate statistics on removals are of course essential for relating population changes to exploitation rates. Commercial fishery statistics for the northeast United States go back to the late 1800s for a few species, but they usually represent only landings for certain ports, and they do not supply adequate information on location of catches and gear used (Rounsefell, 1948). Statistics improved substantially in 1929, when landings were recorded by gear type and location of catch, days absent from port noted, and trawlers classified by tonnage categories so that estimates of abundance (catch per unit effort) could be derived.

However, the abundance records are adequate only for haddock in the 1930s, and yellowtail flounder in the 1940s. From the 1950s on, statistics are adequate for general abundance analysis for most major commercial species (for which there were directed fisheries by New England fishermen), and a much wider area was encompassed through establishment of the International Commission for the Northwest Atlantic Fisheries (ICNAF), which set up a standardized statistical system for the entire northwest Atlantic. There has been a steady improvement in the completeness (number of species) and refinement of statistics since that time. However, it should be noted that complete ICNAF statistical records (including effort data) for abundance analysis that are on file in the computer at the Northeast Fisheries Center go back only to 1963. With the establishment of extended jurisdiction in 1977, further improvements have been initiated, notably in the Middle Atlantic area, where statistics were less complete than in New England waters.

Recreational fishery statistics are far less complete than commercial statistics. National postcard surveys were conducted by the U.S. Census Bureau in 1960, 1965, and 1970. In 1974, the National Marine Fisheries Service (NMFS) surveyed the region from Cape Hatteras to Maine. Only a gross measure of catch is available from these surveys. In 1978, the National Marine Fisheries Service began a more intensive recreational harvest survey, and it is expected to provide more accurate results than previous surveys.

Monitoring Biomass Components of the Ecosystem

Fishery statistics by themselves do not provide adequate information on biomass of all important fish species, nor do they provide adequate prerecruit estimates. Therefore, another source of information is needed which could provide much more complete and unbiased measures of the changes in the size and structure of the finfish biomass as a whole. Similar data are needed on the planktonic and benthic components of the ecosystem if we are to determine how the system changes through time and under different climatic regimes. NMFS established the Marine Resource Monitoring Assessment and Prediction Program (MARMAP) in the early 1970s to provide annual and seasonal monitoring of principal biota on a broad geographic scale. The prototype MARMAP program was begun in 1963, when the Northeast Fisheries Center (NEFC) at Woods Hole, Massachusetts, began a comprehensive bottom trawl survey program designed to provide an annual quantitative inventory of fish populations on the continental shelf off New England.

During the first four years, surveys covered the region from New York to western Nova Scotia (sampling strata 1 to 42; see Figure 1), and were conducted by the NMFS research vessel *Albatross IV*. In 1967, the survey area was expanded to include the Mid-Atlantic Bight region from New York to Cape Hatteras (sampling strata 61-76), and *Albatross IV* was joined by a Soviet vessel as part of a cooperative research program under the auspices of the U.S.-U.S.S.R. Bilateral Treaty on Fisheries in the Mid-Atlantic Area. These surveys showed that with standardized and unbiased sampling methods (a critical feature is random selection of stations within strata) and one or two research vessel cruises per year, it was possible to monitor changes in fish populations with sufficient accuracy to add an invaluable new capability for assessment of the status of major stocks and the effects of fishing. In addition, the surveys added a critical new dimension to the assessment data base in the form of a total finfish biomass index, representing virtually all finfish species, which provided for the first time a comprehensive and quantitative measure of the state (abundance, population structure, species composition) of the finfish component of the marine ecosystem.

The value of these indices for fishery assessment studies and ecosystem studies in general was recognized by scientists in many countries, and by 1970 the bottom trawl surveys had become an integral part of the ICNAF survey program, as well as a major component of the developing MARMAP program, and standardized trawl surveys had expanded to include the entire continental shelf, from Cape Hatteras to the Laurentian Channel (Figure 2), involving the United States, the U.S.S.R., and Canada. Examples of how the survey data are used in assessments are given by Sissenwine et al. (1978).

By 1972, the ICNAF survey program had extended east and north to include the Laurentian Channel and the Gulf of St. Laurence, the Grand Banks off Newfoundland, and the shelf off Labrador and West Greenland, involving Canada, the U.S.S.R., France, West Germany, and the United

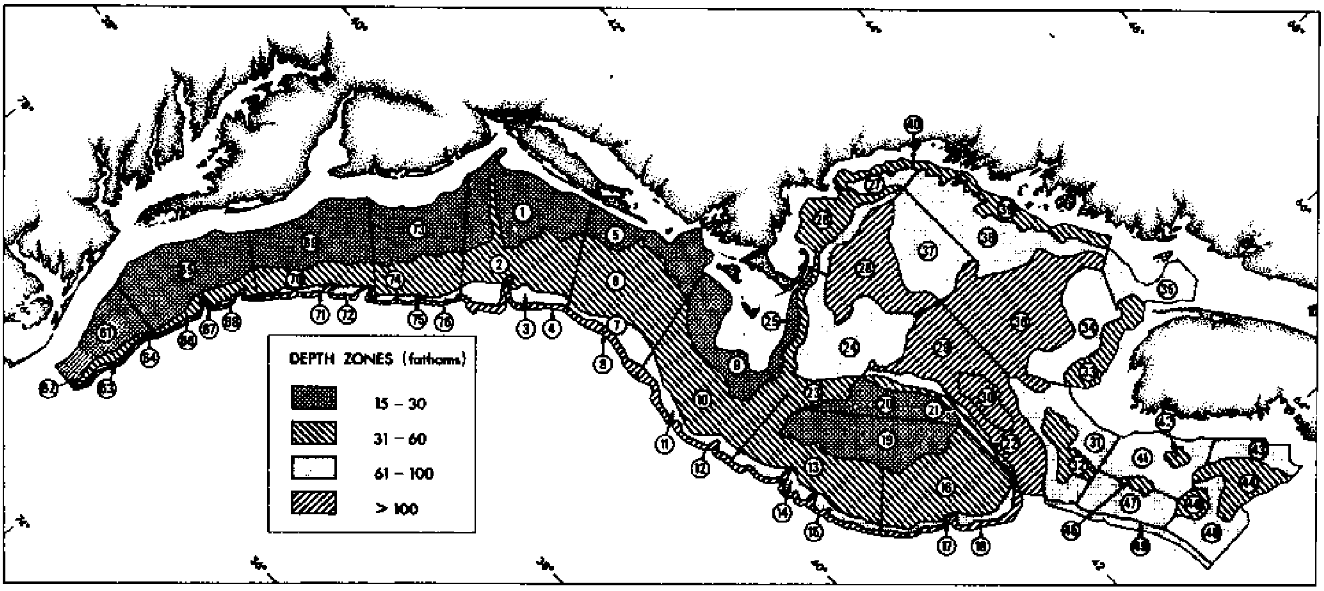

Figure 1. Sampling strata used in offshore bottom trawl surveys since 1963. Comparable depth zones and strata sizes used in stratification of the continental shelf east and south of this region. Stations are randomly selected in each stratum.

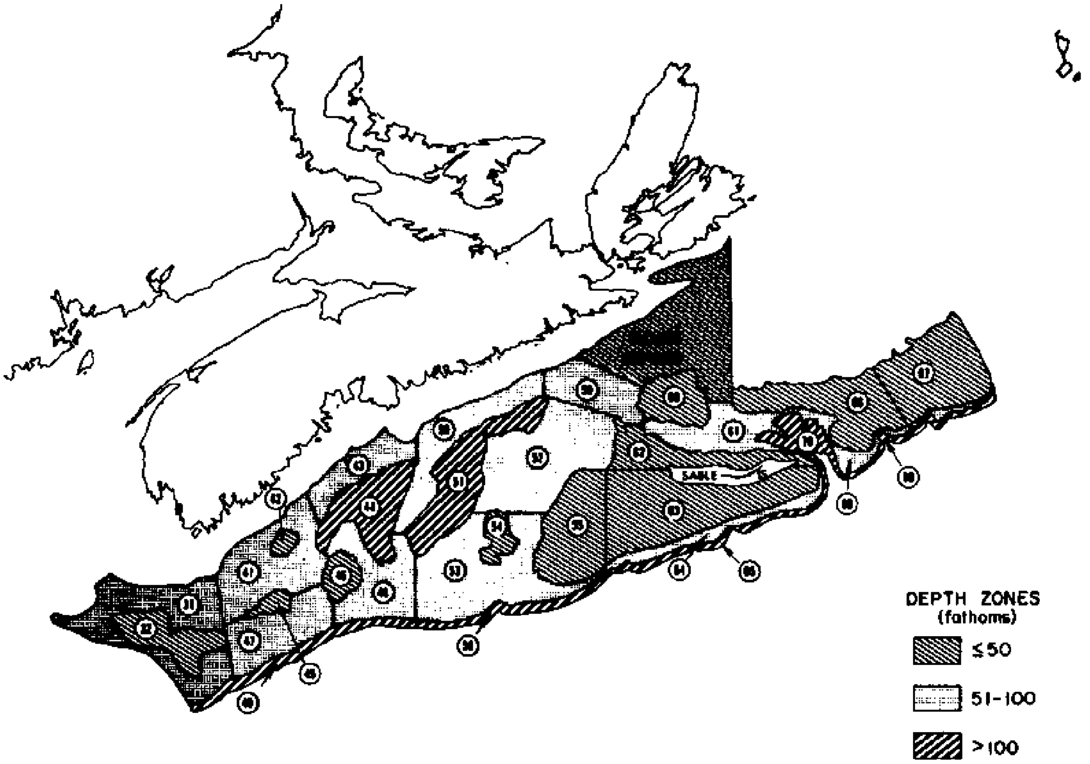

Figure 2. Part of sampling strata used for bottom trawl surveys off Nova Scotia since 1970 by Canada, the United States, and the U.S.S.R. Note that all countries use the same strata except for strata 82 to 85, 90 to 95, where the United States and Canada strata differ slightly.

Kingdom. The MARMAP program had also expanded by extension of the standard offshore survey south of Cape Hatteras to Cape Canaveral (Cape Kennedy) with surveys on the *Delaware II* by the Middle Atlantic Coastal Fisheries Center (MACFC) at Sandy Hook, New Jersey. In addition, MACFC established inshore trawl surveys from Rhode Island to Charleston, South Carolina, using smaller vessels and covering the area from the beach out to the inshore limits (15 fathoms) of the offshore surveys. These inshore areas are nursery grounds for many offshore as well as inshore marine species, both sport and commercial, and therefore are of critical importance in understanding the distribution and population processes of many stocks in relation to changes in fishing and environmental factors (including pollutants).

In 1973, a MARMAP contract was let to the South Carolina Marine Resources Institute for monitoring the region from Cape Fear to Cape Canaveral (Cape Kennedy) in close coordination with the surveys conducted by Woods Hole and Sandy Hook. In addition, a new series of spring bottom trawl surveys by Poland and West Germany was begun in the mid-Atlantic and Georges Bank areas for monitoring semipelagic stocks such as mackerel and sea herring. A rough time table of events since 1963 is outlined in Table 1.

Thus, at the present time coordinated and standardized MARMAP trawl surveys are scheduled for fall and spring over virtually the entire continental shelf off the East Coast of the United States (Figure 3), and comparable surveys are being carried out by ICNAF over most of the remaining shelf off the east coast of Canada. In essence, then, we have a MARMAP-type program established over most productive parts of the entire continental shelf of the northwest Atlantic.

The basic minimum routine data recorded for each haul on trawl surveys include the weight and length frequency of each species of finfish, and selected invertebrate species such as squid, lobster, crab, and shrimp. In addition, scales, otoliths, gonads, and stomachs are collected for continuing assessment and ecological studies, including growth, mortality, age structure, reproduction, and feeding interactions of fish populations. Many other special biological samples are taken in support of other programs, such as the NOAA study on contaminants in marine organisms, as well as ecological studies on many marine species conducted by scientists in other government agencies and in universities.

Table 1. Development of bottom trawl surveys in the northwest Atlantic.

Began in year	*Region surveyed*	*U.S. agencies*	*Other countries*
1963	Hudson Canyon to western Nova Scotia at depths 15-200 fathoms	NMFS (NEFC)	—
1967	Above area *plus* region from Cape Hatteras to Hudson Canyon	NMFS (NEFC)	U.S.S.R.
1970	Above area *plus* remainder of Scotian shelf and Gulf of St. Lawrence	NMFS (NEFC)	U.S.S.R., Canada
1972	Above area *plus* region from Cape Hatteras to Cape Kennedy (including inshore from Long Island to Cape Kennedy at depths <15 fm)	NMFS (NEFC, MACFC)	U.S.S.R., Canada, France, United Kingdom, W. Germany
1973	Above area with region from Cape Fear to Cape Kennedy covered by S.C. (MARMAP contract)	NMFS (NEFC, MACFC) S.C. Marine Resources Dept.	U.S.S.R., Canada, France, United Kingdom, W. Germany, Poland

In 1968, ***Albatross IV*** began taking a plankton tow at each bottom trawl station for the purpose of monitoring the general distribution of fish eggs and larvae. Since it was possible to make the plankton tow simultaneously with the bottom trawl haul, no additional ship time was required in the survey schedule. Since that time, MARMAP has developed operational procedures and preliminary standards for routine monitoring of the biomass and structure of ichthyoplankton communities, and these standards have been followed as far as possible in the "piggyback" plankton sampling on the trawl surveys.

By coordinating the timing of fall and spring trawl surveys, we thus get a general synoptic picture of both demersal fish and ichthyoplankton communities on the entire East Coast during the warm and cold seasons. The large-scale seasonal picture of plankton communities provided by these surveys is a valuable addition to a number of ongoing and more intensive ichthyoplankton studies (e.g., ICNAF larval herring surveys) by providing information on major variations in water-mass pat-

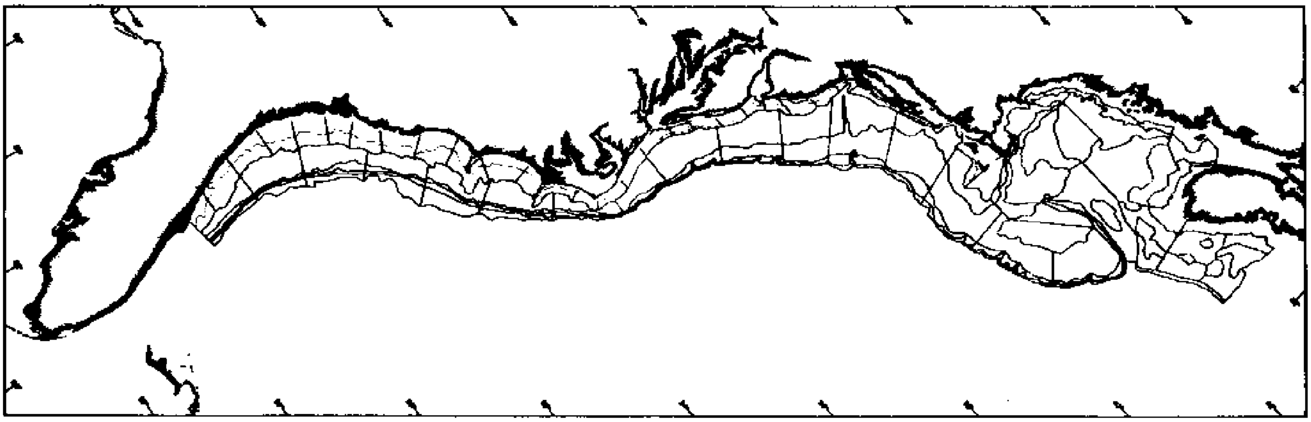

Figure 3. Sampling strata for MARMAP trawl surveys on U.S. East Coast.

terns (through the distribution of associated plankters) which may be related to dispersal and survival of the eggs and larvae of the particular species under study. Since 1977, separate ichthyoplankton surveys have been conducted, and the frequency increased to six or more times a year.

Observations on temperature (surface to bottom) have been taken routinely at each trawl station since the beginning of the trawl survey program. Starting this year, an expanded program of hydrographic sampling is being developed as part of the ichthyoplankton surveys. Standard hydrographic transects are being established at various places along the shelf, and profiles of salinity, temperature, oxygen, and several major nutrients (nitrogen, phosphorus, etc.) are to be taken at stations along these transects during the bottom trawl survey, in addition to the routine temperature record at every station. In this way, large-scale patterns of interactions between coastal and slope water masses, and the interrelationships with plankton, will be better defined, as will major fluctuations in water-mass characteristics which may alter the geographic and inshore/offshore distribution of planktonic communities as well as demersal fishes and invertebrates.

Estimating Production of Biota

The next level of study involves estimation of the actual production of selected components of the ecosystem. In the case of fish production this is done largely on an annual basis, and the techniques and state of the art have been described by Sissenwine et al. (1978). With regard to plankton populations, critical events and production cycles occur over much shorter time scales than for adult fish. A major focus is placed on zooplankton and on larval fish in particular, and here we are considering a time scale of weeks and months to obtain a measure of larval production (as well as survival, etc.) in one season, and usually for only one target species at a time. This is a mesoscale effort and is illustrated by the Georges Bank larval herring surveys.

The approach of the ICNAF survey program was to concentrate sampling in the first 6 months of life on the Georges Bank-Gulf of Maine sea herring stocks. When the surveys were initiated in 1971, the plan was to cover the entire Georges Bank-Gulf of Maine area at least once a month from September to December to monitor larval production and intermixing of larvae from the various spawning sites (see Figure 4 for typical distribution pattern). During the first two years, minimum sampling at each station included oblique hauls with 60-cm Bongos (0.505-mm and 0.333-mm mesh), temperature profiles, and surface salinities. Beginning in March 1973, the Federal Republic of Germany added night sampling of larval herring with Bongos and neuston nets, and in February 1974 the United States began the series of February cruises.

After the formation of the ICNAF Environmental Working Group in June 1974, interest developed in a more comprehensive and intensive investigation of factors controlling success of year classes. In the autumn of 1974, paired 20-cm Bongos with smaller mesh sizes (0.253 mm and 0.053 mm) were added to the standard 60-cm Bongos, and in subsequent years 0.253-mm and 0.165-mm mesh nets were used on the 20-cm Bongos. In May 1975, the Working Group recommended that in addition to monitoring larval herring production more emphasis

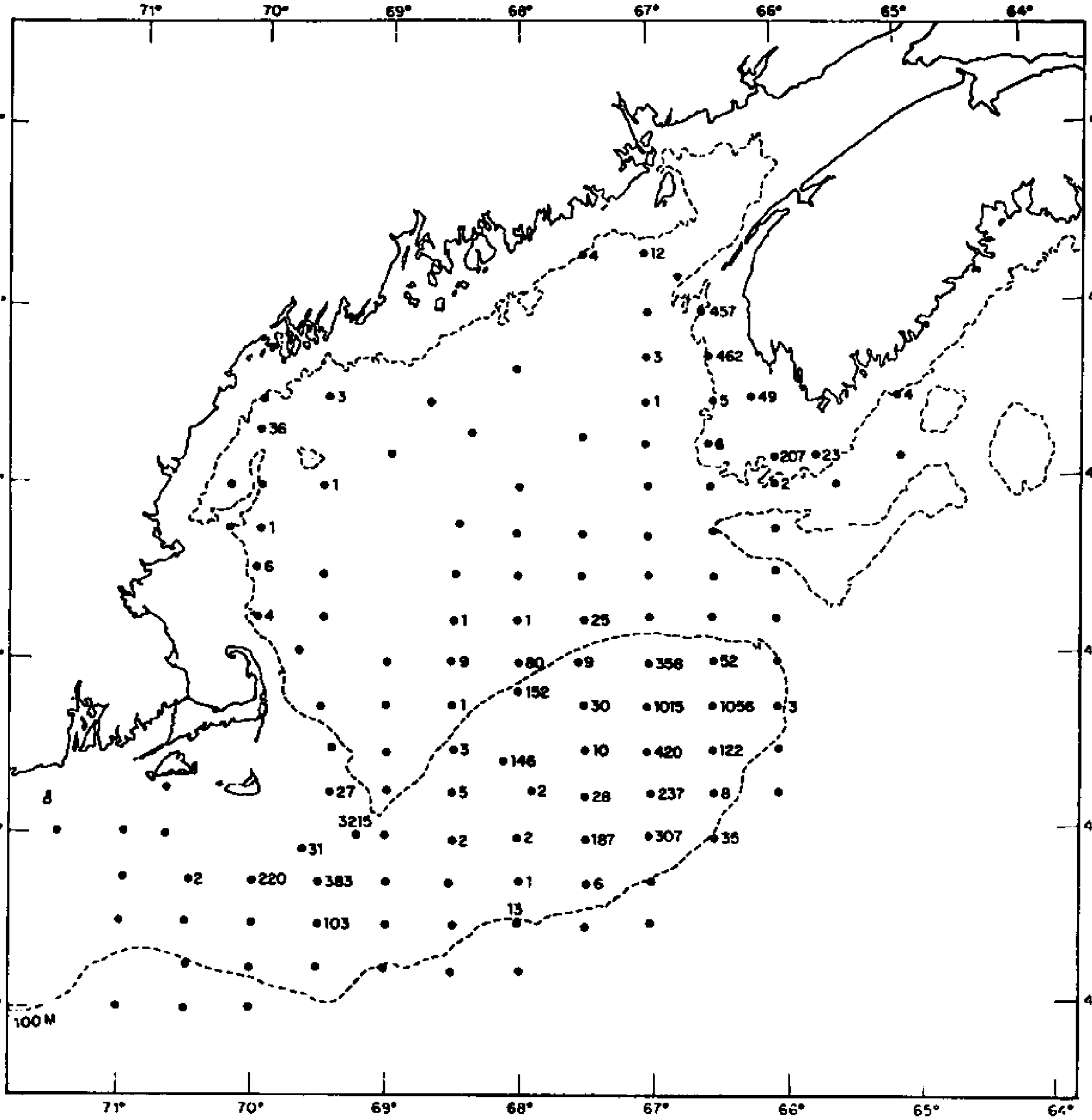

Figure 4. R/V *Wieczno,* October 2-October 28, 1972. Larval herring (total no/ 10 m^2).

should be given to studying circulation in the Georges Bank-Nantucket Shoals area, and that concurrent studies of primary and secondary production should be initiated, as well as fine-scale patch studies. Thereafter, emphasis shifted to the Georges Bank-Nantucket area alone, since vessel support was insufficient for intensive sampling of the whole region (see Figure 5 for revised station pattern). Sampling was expanded to include more complete hydrographic coverage (temperature, O_2, and salinity profiles at each station), and also nutrients, chlorophyll, and primary production when possible.

The program has continued along these lines to date, but only a small fraction of the total data base has been analyzed. Analysis of nutrients, chlorophyll, and primary production is still in progress. Preliminary temperature and salinity plots have been completed for most cruises, and the data has now been entered into the National Oceanographic Data Center (NODC) computer. Analysis of the full-time series of plankton samples so far has been restricted largely to the 0.505-mm mesh series and to the length frequency and distribution of herring larvae. Sorting of the ichthyoplankton from the 0.333-mm mesh samples was completed by the Polish Sorting Center in December 1977, but the zooplankton components will take at least another year. Only broad-scale changes in structure and abundance of invertebrate zooplankton populations can be derived from these surveys, since significant segments of the population cycles, juvenile stages in particular, are missed with the monthly or bimonthly spacing of cruises.

Very few quantitative phytoplankton studies have been done in the offshore areas. In recent years (1975 to 1976), primary production estimates were made on Georges Bank in conjunction with the ICNAF larval herring surveys. A preliminary report on this work indicated unexpectedly high production values throughout the year, which may

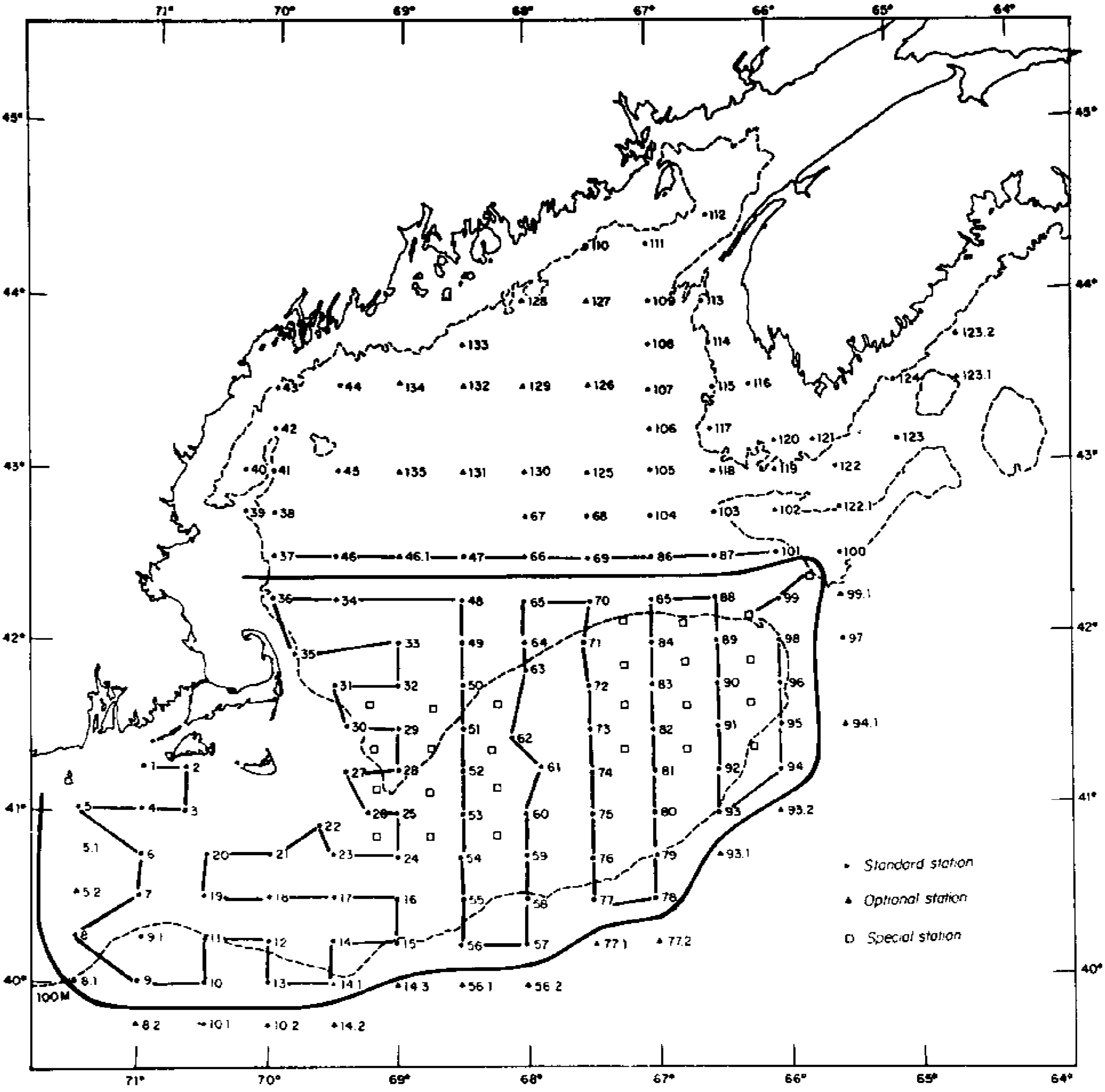

Figure 5. ICNAF larval herring survey sampling stations and cruise track. Coverage within heavy solid line emphasized.

Table 2. Current status of knowledge of biotic components of northwest Atlantic ecosystem and present research efforts. (Two levels of knowledge and activity are indicated: ✓ [limited] and X [reasonably comprehensive]. Numbers in parentheses refer to time and space scales involved.)*

	Status of knowledge				
Biota	Species list	Biomass inventory	Annual-seasonal monitoring of biomass and structure	Short-term predictions, abundance fluctuations; mostly individual species	Long-term predictions of multispecies population; understanding dynamics
Birds-mammals	X	✓	✓		
Apex predators (large sharks, etc.)	X	✓	✓		
Fish					
adult	X	X	X (1)	X (1)	
juvenile	X	✓	✓		
larvae	X	X	X (1,2)		
Benthos	X	X			
Zooplankton	X	X	X (1,2)		
Phytoplankton	✓	✓	✓		
Bacteria	?				

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*1. *Macroscale; annual-seasonal variations, shelf-wide, population scale.*

2. *Mesoscale; within season variations, selected geographic regions, individual stock scale (e.g., fish stocks).*

3. *Microscale; hours to 10-day variations (meteorological and oceanographic event scale), restricted areas, small biological units (e.g., plankton patch).*

help explain the high productivity for other levels of the food chain (Cohen and Wright, 1978). More detailed studies of primary and secondary production by NEFC are in progress this year in cooperation with the U.S.S.R. and the Brookhaven National Laboratory.

Process-Oriented Studies

The fourth level of study is designed to identify mechanisms which control critical phases of the production cycle of selected components of the ecosystem. An example of such a "microscale" study is the larval herring patch study scheduled for October 1978 on Georges Bank. The purpose of the patch study is to gain a basic understanding of short-term physical and biological mechanisms controlling growth, survival, and dispersal of recently hatched herring larvae and their food organisms from the northeast Georges Bank spawning ground — and the related question of possible mechanisms for their retention on Georges Bank. The proposed study would involve intensive sampling of the horizontal and vertical structure of a patch of larvae by several vessels working simultaneously for a period of 3 to 4 weeks, beginning in October 1978, and include direct measures of water motion using moored current meters, drifting buoys with drogues, and dye experiments. At the present time, up to five vessels are expected to participate in the 1978 patch study. One vessel would do hydrographic and current studies, and another vessel would monitor patch boundaries by continuous high-speed sampling with plankton nets. A third would sample vertical structure and horizontal patchiness with opening-closing samplers, and a fourth would study fine-scale structure of phytoplankton and zooplankton with a plankton pump. A fifth vessel would do quantitative sampling of zooplankton (bottom to surface) in the patch using standard Bongos. At the same time, a sixth vessel is scheduled to provide broad plankton-hydrographic survey coverage for the entire Georges Bank-Gulf of Maine region, similar to that of the ICNAF larval herring survey.

It seems clear that the "microscale" approach will be necessary in order to identify controlling mechanisms in plankton populations. However, the answers are not likely to emerge quickly, because of the complexity of the system and the resources required to conduct such interdisciplinary studies. The implication is that development of predictive fish-production models that incorporate climatic information is going to be a long process.

Summary Status of Knowledge

A very rough outline of the general status of knowledge for the biological components of the marine ecosystem is presented in Table 2. For each of the major biological communities, the current status of information is indexed under five levels increasing in complexity from left to right (from mere knowledge of species composition to the understanding of population dynamics at the multispecies level adequate for long-term predictions). Obviously we have a long way to go. The most likely payoff in terms of developing predictive models for fish production which include climatic factors will be through expansion of knowledge in the plankton and larval fish communities and through an understanding of how they are controlled by physical oceanographic processes.

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Use of Environmental Data in the Prediction of Marine Fisheries Abundance

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Introduction

Prediction of the distribution and abundance of fish stocks has long been an art, but only recently have significant efforts been expanded to make it a science. Environmental information has been used in artistic and scientific attempts at prediction. However, one of the oldest and most successful examples of prediction of small-scale distribution was made by an itinerant Jewish carpenter about two thousand years ago (New Testament, 33 A.D.), apparently without environmental inputs. It is doubtful that this performance can be matched by present-day fishery managers, for they lack the special insights of this early practitioner.

Other examples of nonscientific predictions of fish distribution can be found in folk legends regarding the timing of fish migrations, some of which involve environmental inputs. For example, Edwards (1965) tells of a belief held by old-time Rhode Island fishermen that the arrival of scup *(Stenotomus crysops)* was concurrent with the flowering of dandelions. Long Island and Virginia fishermen on the other hand predict the arrival of shad *(Alosa)* with the flowering of the shad bush, and weakfish *(Cynoscion)* with the dogwood or lilac. Further, the interval between flowering of the two trees is an indicator of the success of the weakfish fishery.

Early attempts at scientific prediction of fish abundance using environmental input data included Walford's (1938) efforts to relate the distribution of haddock eggs on Georges Bank to the density structure of the water, Sette's (1943) efforts to relate Atlantic mackerel year-class strength to wind conditions during the pelagic larval stage of development, and Pearson's (1948) study relating fluctuations in blue crab catch to discharge volume in Chesapeake Bay tributaries.

State of the Science and Complications

Recent descriptions of the status of the application of environmental information to fishery predictions have been presented by McHugh (1976) and Johnson and Seckel (1977), principally in the form of case-study examples. Most of the examples chosen demonstrated logical, conceptually linked relationships which reflect true ecological interactions; however, these presentations, plus the much more detailed description of studies in the northeastern Atlantic and adjacent seas by Cushing and Dickson (1976), show that most studies linking fishery variations to short-term and long-term climatic changes are still predominantly empirically derived inferences. Looking further into the literature of fishery biology and oceanography, we can find many accounts of correlations of fishery landings and environmental data which are hardly tenable as reflections of true ecological relationships, in spite of the high statistical correlation coefficients some may involve (Dow, 1964, 1969, 1977; Flowers and Saila, 1972).

In these studies, climatic and fishery yield data were linked in a purely statistical fashion, with no attention paid to the development of a conceptual model or an ecological explanation of the interaction between them. They appear to be a search for high correlation coefficients, obtained by multiple regression analysis and trial-and-error adjustment of lag times so that sufficiently high coefficients appear. Dow (1964) and Sutcliffe et al. (1977), for example, lagged temperature cycles until they fit the biotic cycles. This was done with no explanation of cause and effect. The justification appears to have been based upon improved correlation coefficients. The results of studies of climate and fisheries would be far more relevant and useful if they were to *begin* with a conceptual model of the interaction between the environment and the subject organisms and if statistical techniques were *then* applied to the data. "Any fairly linear trends could be related to almost any activity of man because most of man's activities are changing in a cumulative manner. It would be no more than flippant to relate plankton trends to the illegitimacy rate in teenage girls (because, we hope, nobody would impute a causal relationship) but it might be dangerously misleading to relate them to the quantities of suspended matter in the atmosphere, or the rates of industrial production of mercurial fungicides and organochlorine insecticides (because there are many people who would undoubtedly impute a causal relationship without the essential evidence from all the inter-acting complex of factors that produce variability in nature)" (Glover et al., 1974).

The environmental variable or variables selected as significant for correlation with biological abundance or distribution data may not be the truly causal factors sought. They may be indices of the causal factors, or, even worse, they may be unrelated to the causal factors. Temperatures of water or air are frequently used in studies of climate and fish abundance, mostly because temperature time series are the most abundant. In many cases, however, temperature is not the causal factor at all, but is once or twice removed from it. For example, as pointed out by Laurs and Lynn (1977), the distribution of forage in temperature *gradient* zones may be a far more important factor in stock distribution than an actual response to the temperature field by the tuna.

Often the most relevant data sets for climate/fisheries studies are ocean temperatures of currents at the appropriate depths and recruitment or year-class-strength time series. Rarely are two matching sets available, and "proxy" data must be used. Such proxy data may be temperature extrapolated from air temperature records at some distant coastal weather station, currents computed from atmospheric pressure gradients (Nelson et al., 1977), and fishery catch statistics, sometimes converted to catch per unit effort. Drawing conclusions from correlations of sets of such proxy data can be misleading and unwarranted. Unfortunately, the practice of using proxy data is likely to continue to be prevalent, because time series of the primary data required are rare. As for environmental data, time series of subsurface measurements are practically nonexistent, and surface data banks often contain only series of surface temperature and wind data. Time series of biological data are even scantier, with direct assessments of fish abundance very rare. Most estimates are generated from fishery catch statistics, often without effort data.

The use of proxy data can be acceptable or desirable in some circumstances, however, if there is a firm bridge of knowledge from the proxy data to the causal factor to the organism. For example, atmospheric pressure gradients may be acceptable and desirable proxy data for year-class-strength correlations, because the gradients produce the winds that provide the transports of water which carry larvae to estuarine nursery areas of the proper salinity and temperature (Nelson et al., 1977; Chase, 1955).

Many fish stocks, especially the filter-feeding pelagic species, undergo wide variation in population for other than environmental reasons. With those fishes, density-dependent factors such as cannibalism (on eggs and larvae by adults) and competition for food may produce lower survival and recruitment from dense populations of spawners than from smaller populations. These density-dependent factors are manifested in quasi-parabolic spawner-recruit curves for many species. The composition of the population in most stocks under heavy fishing pressure changes from older to younger fish. When the stock size is large, recruitment often exhibits wide ranges of inter-annual fluctuation. These fluctuations may not, however, be significant to the stock. At lower stock sizes, the range, or variability, in recruitment is less, but of greater significance to the stock, as poor recruitment may be matched with poor environmental conditions. In some fisheries, these and other biological factors are relatively well understood and are accounted for in yield models. Nevertheless, such fisheries occasionally undergo unexpected and unexplained variations in year-class strength, which are generally attributed to unnamed environmental factors. "Environmental factors are obviously the major controlling forces, but the present state of knowledge concerning the influence of these factors is inadequate for assessment use" (Mackerel Fisheries Management Plan, Mid-Atlantic Fisheries Management Council, March 1978).

All too often, data series collected over several decades are of low quality, totally or in part. In biological series, economic factors which may strongly affect fishing effort could be totally overlooked in catch data: perhaps no distinction is made between abundance and availability to a gear type; significant changes in harvesting technology may be overlooked in catch-effort data (Bell and Pruter, 1958); and in some fisheries the fishermen may deliberately falsify catch or location data to conceal true incomes or violations of area restrictions.

In environmental series, the design of instruments used in measurements might be changed one or more times during the period of record (e.g., from mechanical bathythermographs to expendable bathythermographs), the measurement site might be changed, or technological change might occur in the vicinity of the measurement site (deeper cooling water intakes on larger ships or industrial thermal effects at shore stations). Early data series may not have been quantified at all, such as estimates of sea state or classifications of "good" or "poor" fishery yields.

In addition to problems with poor quality in time series data, the lengths of the series frequently are too short. It is difficult to find government agencies or business enterprises which will remain dedicated to monitoring variations for more than a few decades. It has been said that the interest span of some branches of the United States government is about 4 years. Fortunately, this is an exaggeration, but there is a problem with maintaining continuity of monitoring activities in the face of funding cuts, reorganizations, and staffing freezes.

Most physical oceanographers who have sought to work with marine biologists on ecological studies have encountered at least one who doubts the utility of physical and chemical data. Some population dynamicists begin each study with a set of assumptions, including the assumption that environmental variation has no significant effect on the abundance of the species being studied, to simplify the modeling effort. It is doubtful that there is any species whose variations in abundance are not influenced by environmental changes.

Based on a review of about 50 publications (see "Annotated Bibliography") concerning climate/fisheries interactions, the following complications appear to be common:

(1) There is a lack of established causal relationships in many fisheries.

(2) Scientists frequently must resort to use of proxy data, environmental and biological.

(3) The major variations in a fishery may not be caused by environmental factors.

(4) The quality of data time series, especially biological, is often poor and the time series are frequently too short.

(5) There is a frequent lack of interest among fishery biologists and managers in using environmental data and relationships for predictive or explanatory purposes.

Biological Considerations in Design of Investigations

The priority criteria for selection of species or stocks for study are generally determined by management needs and not by the potential for success in climate studies. Nevertheless, there are several points to consider which, if addressed, should increase the chances for success in developing climate/fisheries studies. These considerations involve an understanding of those biological processes that are forced by the environment and produce variations in distribution or abundance of a species.

The length of time spent in the water column as a plankter is one of the most critical considerations. A species with a long larval existence is susceptible to predation by filter feeders, changes in food abundance (Lasker, 1978), and currents and winds (Nelson et al., 1977). Species with a fairly short pelagic existence are less likely to show year-to-year fluctuations as they pass quickly from this somewhat precarious existence. Cushing and Dickson (1976), on the other hand, discuss the concept of the match/mismatch between spawning and the spring phytoplankton bloom, and point out that a shorter larval period could lead to an entire year class missing the spring bloom. Cushing (1972) and Bannister et al. (1974) cite an example where the 1963 year class of plaice was excellent following a cold winter, which delayed both larval metamorphosis and the spring bloom. The bloom, which was intense once it did occur, provided a strong match with the larvae, resulting in a strong year class in spite of the prolonged larval period.

Studies on the hard clam in Virginia waters (Castagna, personal communication) have shown that there is also better recruitment following a cold winter. In this case, the winter delays spawning, with the result that the larvae are in the water for only a short time, and thus provide a mismatch with predators. Spawning after a warm winter is more protracted, and larval predators have more time to feed.

In short, a long larval period generally makes a species more susceptible to environmental change, and hence more likely to show interannual fluctuations.

From the foregoing, it also appears that the larval period is affected by the severity of the winter (Cushing, 1972; Bannister et al., 1974; and Castagna, personal communication), and as such the winter/larvae relationship is an important consideration.

The fecundity of a species is an important consideration, as more fecund species, such as cod, tend to be stabilized at high population densities. Higher reproductive capability offsets density-dependent factors, such as cannibalism, but can lead to wide fluctuations in abundance if environmental variations increase the egg or larval mortality.

Cannibalism may be a stabilizing factor when large year classes of juveniles are preyed upon by the adult stock, thus limiting their number. The converse follows when large year classes become adults. This relationship has been demonstrated for Alaska pollock (Laevastu and Favorite, 1976). It would follow, then, that noncannibalistic species may be better candidates for examination, as this source of biotic variability would be removed.

Variability in abundance and distribution is greatest near the northern or southern limit of a species' range, or, as in the case of estuarine species (oyster), near the limits of its salinity range. Temperate-zone stocks demonstrate a greater interannual variability than tropical species, as the annual environmental fluctuations in the temperate zone are greater, and temperate stocks have a short spawning season when compared to tropical species that demonstrate a protracted spawn or one that occurs several times a year. For this reason, the timing of events in the temperate zone is critical, as spawning for most species occurs during the time of greatest environmental change (e.g., in spring). This lends further credence to the match/mismatch theory of Cushing and Dickson (1976), which states that the larval period must coincide with the appropriate stage of the spring bloom.

The trophic level occupied by a species or the level at which it feeds is important. The lower the position on the trophic chain occupied by a species, the more rapid its response to environmental change. This is true both of forage plankton (including ichthyoplankton) and of species that feed on them (e.g., herring, menhaden, anchoveta).

A heavily fished or overfished stock is more susceptible to environmental fluctuations than is a more stable or underutilized stock. It has been pointed out in the Mackerel Fisheries Management Plan of the Mid-Atlantic Fisheries Management Council (March 1978) that recruitment is generally independent of stock size except at low levels of abundance, and that here "it is clear that environmental factors are significant in controlling recruitment" (p. 91).

Age is an important consideration, as young fish are often eurythermal and euryhaline. Best examples of these are the "estuarine-dependent" species that as juveniles inhabit inshore areas where temperature and salinity fluctuate widely. As adults they move offshore into the higher salinity waters of the shelf or open sea where variations are slight. The juvenile stages, able to tolerate the lower salinities and higher summer temperatures, are safe from many adult predators (Gunter, 1967).

The completeness and availability of the biological data base is as important as the environmental base. Unfortunately, adequate biological data bases for climatological studies do not exist in most cases. The extant data are generally in two forms, catch or landings, or assessment data from surveys.

Most catch data exist without supporting effort data; hence, they are not sufficiently quantitative. Further, the data bases do not carry accurate data on recreational catches, which may exceed the commercial catch by 3 to 10 times.

Catch and landing data are generally reported by calendar year. For example, the New York bay scallop fishery runs from October to March. The October to December 1977 segment is reported with the catch of "last year" (January to March 1977), and this season's (January to March 1978) with next year's (October to December 1978). Consequently, interannual variations may be averaged away. Data are available, however, over 20- to 30-year periods, which lends itself to climate-scale analyses.

Assessment data, needed for recruitment estimates, are often of doubtful accuracy due to sampling methods, and are generally over too short a time period for climatological studies. These data, however, can be collected for specific areas such as spawning grounds, during specific seasons, and with concurrent environmental data. Additionally, biologically significant measurements and indices can be made (e.g., condition factors, food habits, annuli measurements, gonad indices).

It is impossible when examining climate-scale bio-environmental interactions to go back and make different measurements. Generally, physical environmental parameters can be inferred from other measurements extant in data bases, even when not actually measured themselves, but this is not so with the biological. If, for example, one has 20 years of length-frequency data for a species and then decides that the winter condition factor (a length/weight relationship) is the critical determinant, it is not possible to go back and make the needed weight measurements. It may be possible, however, from the records at the National Climatic Center, to retrieve minimum winter temperatures and their duration, or ice cover, all of which influence the length/weight relationship (condition factor).

Bio-Environmental Considerations in Design of Investigations

Successful studies of the effects of climatological variations on fish populations require bases of time-series environmental data of high quality. Occasionally, these time series are available for several decades in a study area, but more often the data series are too short in duration, of unacceptable quality, or in the wrong geographic region. In such cases, the inadequate data bases may be used to perform rough tests of hypothesis, or proxy atmospheric data, which are available over wide global areas where no ocean time series exists, and can be used with caution to infer ocean changes if the sea/air linkages are understood. Further attempts to pursue promising theories will require the establishment of environmental monitoring programs for a period of many years. Because such programs are costly and difficult to justify to managers, marine scientists usually are forced to make do with existing data sets or ongoing monitoring programs. Therefore, an inventory of the environmental data available in a potential study area is of critical importance in deciding whether or not to begin a fishery-climatological study.

An understanding of the causal relation between environmental forcing and biological response is a prerequisite to the selection of the species or stock in question. Far too often, for example, we select temperature or temperature anomalies as our independent variable, without understanding the link between environment, in this case temperature, and biota.

One can demonstrate a correlation between anchovy-recruitment success and sea surface temperature off California, which would be merely fortuitous. Lowered sea surface temperatures have no effect on recruitment, but are an *indication* of upwelling, which, if present during the anchovy postlarval stage, disperses the proper concentration of dinoflagellates and encourages the bloom of diatoms, which are of no nutritional value to the larval anchovy (Lasker, 1978). Reduced temperature is merely a manifestation or index of upwelling.

A fact that is often missed in looking for bio-environmental relationships is that the environmental fluctuation may be affecting the abundance and distribution of the forage and not the stock being examined. The relationship of the Pacific albacore to the coastal upwelling fronts is an example in which there is a response of the albacore to the distribution of their forage and not to the temperature gradient itself (Laurs et al., 1976). The forage too is responding to changes in planktonic abundance associated with the front and not to a physiological response to the thermal field.

Some pelagic or planktonic forms are indicators of climatic-scale events about to happen. The appearance of Indonesian milkfish larvae off the coast of Peru is an indicator of an impending el Niño. Its appearance is explained (Cushing and Dickson, 1976) by the relaxation of the Southern Hemisphere trade winds and subsequent strengthening of the equatorial counter current, which brings tropical western Pacific waters to the eastern Pacific.

River runoff is a popular variable to examine when studying coastal species. But what is the effect of runoff? In the case of the Chesapeake Bay blue crab population, it is a factor in a complex cycle with timing of utmost importance. A dry summer provides a large high-salinity spawning ground at the mouth of the bay. This must be followed by a wet fall with high runoff to provide a large low-salinity nursery ground. The larvae need high salinity, and the juveniles low salinity. It is the areal extent of the spawning or nursery ground that is of importance; the effects of salinity are secondary (Van Engel, personal communication).

Recent advances in the field of marine resource prediction have not been with parameters such as temperature or salinity but with dynamic processes, the forcing functions such as upwelling indices or indices of Ekman transport. These successes suggest that we are developing better data sets and that we are developing a better understanding of how the physical environment forces changes on the biological side of the system.

Studies relating catch data to physical environmental data are hindered by the fact that the environmental data are often point source (e.g., Ambrose Light Tower), whereas the catch data are from large areas (ICNAF or FAO statistical regions, for example). Biota/environment relationships are masked, due to the geographic disparity.

Future efforts directed at predicting the abundance and distribution of stocks must give careful consideration to the biotic factors that act as forces, how they occur, and what the forcing function is. Without an understanding of the dynamics of the biota/environment link we will never progress from statistical or empirical models to conceptual and mechanistic models.

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   "The effects of other variables such as economic conditions, changes in fishing practices and the extent of the removals by man should be accounted for. The possibility of fortuitous relationships must be discounted by exhaustive tests of the representativeness and adequacy of the environmental data, and equal care must be exercised in the selection and evaluation of the fishery data, particularly that of catch per unit effort."
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El Niño years	Non-el Niño years
(1) 1972 SST up 5°C	Average SST
(2) High heat supply in equatorial Pacific	Normal
(3) Intensified Hadley circulation	Normal circulation
(4) Increased flux of angular momentum	Normal
(5) Intensified wind-lat. westerlies	Normal

   A trough over the eastern U.S. in 1958-59 resulted in the coldest winter to that date since 1917-18. 1939-40 also cold, same 700 mb pattern. 1948-49 warm, with reverse pattern at 700 mb (ridge over eastern U.S.). When (-) off East Coast, then (+) (e.g. '58) warm off California — cold affects Gulf shrimp.

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Fish near northern or southern end of range show greater response to climate variation than do those in center. Clupeid and salmonids react quickly, whereas gadoids don't. Perhaps due to fecundity — more fecund species tend toward stabilization.
Fish with fixed spawning cycles (generally north of 40°N) are more susceptible than those south of 40°, where productivity continues all year.
Spring bloom often occurs at the same time each year, but spring spawning can vary. Match or mismatch is important, as cold water often delays larval abundance — spring bloom is more photoperiod-dependent until productivity is high. Russell cycle during early 30s to 40s general warming, most profound in 1926-35. Reversed from 66 to 72 by general cooling. Named after Russell, its "discoverer." Ecosystem response is step-like, with sudden changes at beginning and end of cycle.

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Dungeness crab '63, '64, '68
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(2) Duration of abundance has decreased from 7.25 to 6.0 months.
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(3) Reduced water flow, hence O_2.
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Heavy discharge during spawning is bad, and light discharge is good.

34. Peterson, W. T. 1973. Upwelling indices and annual catches of Dungeness crab, *Cancer magister,* along the west coast of the United States. Fish. Bull. 71:902-910.
Empirical relationship between intensity of upwelling and crab fishery. Strong crab catch lags strong upwelling index by 1.5 years.

35. Quinn, W. H. 1976. Use of southern oscillation indices to assess the physical environment of certain tropical Pacific fisheries. In: Proceedings of the NMFS/EDS Workshop on Climate and Fisheries, April 26-29, 1976. pp. 50-70.
Anomalous equatorial Pacific meteorological and oceanographic conditions (e.g., el Niño) are the result of certain large-scale changes in atmospheric and oceanic circulation. These changes appear to be closely associated with variations in amplitude and period of an irregular interannual fluctuation in the atmosphere circulation called the Southern Oscillation. Changes in the Southern Oscillation are monitored and predicted through time series of atmospheric pressure indices.

36. Rae, K. 1957. A relationship between wind, plankton and haddock brood strength. Bull. Mar. Biol. 6(38):248-269.
Haddock recruitment is dependent upon wind functions. Larvae can be carried over open water, and fail to settle out.

37. Russell, F. S., A. J. Southward, G. T. Boalch, and E. I. Bitler. 1971. Changes in biological conditions in the English Channel off Plymouth during the last half century. Nature (234):468-470.
Period of 1920 to 1940s shows reduction in herring, cod, and ling coincident with reduction in *Calanus* and phosphorus (0.8 to 0.4).
During period 1940s to 1964, pilchard eggs were abundant. In 1960s to 1971, pilchards' eggs disappeared again, and herring, cod, and ling reappeared.
Suggest "warming of Arctic would affect circulation in North Sea and let Atlantic Ocean waters extend further north." With winter PO_4 as link, winter-hatched herring are (were) inversely related to pilchards hatched the following summer.

38. Seckel, G. 1972. Hawaiian-caught skipjack tuna and their physical environment. Fish. Bull. 72(3):763-787.
Seasonal shifts in Pacific water masses can be used as a predictor for skipjack abundance in the Hawaiian live bait fisheries. Temperature shifts in April is the best predictive index. Early shift, good year; late shift, bad year.

39. ____. 1976. Climate oceanography in the Pacific. In: Proceedings of NOAA Symposium on Ocean Aspects of a Climate Program. Boulder, Colo., May 1976. 35 pp.
Time-series data are necessary in order to discern climatic-scale events. Oceanographers find work difficult due to lack of marine time series and lack of any ocean data. Atmospheric proxy data exist with good continuous series and with good coverage.

40. Sette, O. E. 1943. Biology of the Atlantic mack-

erel *(Scomber scomberus)* of North America. Fish. Bull. 50(38):149-237. Fish and Wildl. Serv. of the U.S. Dept. of Interior.
Pursues hypothesis that "infant mortality" is the key to year-class success. Studied 1932 year class by extensive field sampling of eggs, larvae, and postlarvae; year class failed, so looked for reason. Found that no single stage of development was outstandingly critical, but seemed to be high mortality rate throughout. Probable causes: 1) dearth of food (low zooplankton population), 2) unfavorable winds from northeast drove larvae away from nursery grounds off southern New England instead of toward them as southwestern wind would.

41. Simpson, A. C. 1953. Some observations on the mortality of fish and distribution of plankton in the southern North Sea during the cold winter, 1946-1947. J. du Conseil, Vol. 19. pp. 150-177.
    In January 1947, high pressure system over Scandinavia gave high easterly winds over North Sea for 4 weeks. Displaced several species from their spawning grounds (dabs, cod, flounder) and delayed hatching.
    Dead fish (cod, plaice, and dab) found. Same in 1929.
42. Sissenwine, Michael P. 1977. A compartmentalized simulation model of the southern New England yellowtail flounder, *Limanda ferruginea*, fishery. Fish. Bull. 5(3):465-482.
    Develops a complex simulation model of the yellowtail fishery. Used input of average annual air temperature at Block Island along with many biological variables. Model accounted for 83.5 percent of variability in yield, using linear stock-recruitment function, and 83.2 percent using density-independent function.
43. Southward, A. J., E. I. Butler, and L. Pennycuick. 1975. Recent cyclic changes in climate and in abundance of marine life. Nature 253:714-717.
    Processed sea temperatures at International Hydro. Sta. E-1, south of Plymouth, England, and fishery catch-effort data (hake and cod) with Fourien analysis and auto-correlation. Found 10- to 11-year cycles in both sets. Also correlated temperatures with pilchard egg population, postlarval clupeids, and phosphate concentrations.
44. Storrow, B. 1947. Concerning fluctuations and the teaching of ecology. Report of the Dove Marine Laboratory. Third Series, No. 9. pp. 7-580.
    Nineteenth-century phases for bluefish and weakfish. Bluefish phase associated with seals, capelin, and basking sharks; weakfish phase with herring, mackerel, and menhaden. Bluefish, warm in Europe; weakfish, cool in Europe.
45. Sutcliffe, W. H., Jr., K. Drinkwater, and B. S. Muir. 1977. Correlations of fish catch and environmental factors in the Gulf of Maine. J. Fish. Res. Bd. Canada 34:19-30.
    Correlated catches of 17 species in ICNAF Statistical Area 5 with water temperatures in northern Gulf of Maine and Bay of Fundy. Consideration of fishing effort and selecting best lag times improved the correlations. No discussion of cause-and-effect interactions between temperatures and catches.
46. Taylor, Clyde C., Henry B. Bigelow, and Herbert W. Graham. 1957. Climate trends and the distribution of marine animals in New England. Fish. Bull. 57:293-345.
    Discusses warming trend in 1900-40 period to sea water temperature trends at Boothbay Harbor. Related landing statistics for mackerel, lobster, whiting, menhaden, and yellowtail flounder to the air temperature and water temperature records. Relates range extensions of southern species to temperature trends. Points out weakness in the causal inferences which might be drawn from these data.
47. Templeman, Wilford, and A. M. Fleming. 1953. Long term changes in hydrographic conditions and corresponding changes in the abundance of marine animals. Int. Comm. Northwest Atl. Fish. Annual Proc. 3:78-86.
    Points out lack of good long-term set of hydrographic data in ICNAF areas 2 and 3. Uses air temperature record at Jorbay Airport, St. Johns, Newfoundland (1872-1952), and water temperature record at St. Andrews, N.B. (1920-52). Visual correlation of temperature data (annual) with rough abundance data (catch, sightings) for mackerel, lobster, squid, billfish, capelin, and cod.
48. Uda. 1952. On the relation between the variation of the important fisheries conditions and oceanography conditions in the adjacent waters to Japan. J. Tokyo Univ. Fisheries 38(3):364-389.
    Poorest catches of Hokkaido herring when cold winter 4 years earlier. 1866, 69, 84; 1902, 05, 13, 26, 35, 45.

Herring lay eggs along shore and are susceptible to cold.

49. Walford, Lionel. 1946. Correlation between fluctuations in abundance of the Pacific sardine *(Sardinops caerulea)* and salinity of the sea water. J. Mar. Res. 6(1):48-53.
    The size of a year class of sardines correlates with average daily summer surface salinities from 1934 to 1941. Salinity is an index of upwelling. Year classes were best for the years where salinities were high.
50. Welch, Walter R. 1968. Changes in abundance of the green crab, *Carcinus maenas* L., in relation to recent temperature changes. Fish. Bull. 67(2):337-345.
    Compared water temperature records at Boothbay Harbor with measures of green crab abundance and soft clam harvest. Temperatures declined after 1953 peak. Green crab abundance decreased and soft clam catch increased. Crab response apparently is physiological, both on adult survival and reproductive success, and the reduction of crab population reduced predation on soft clams.
51. Wickett, P. 1975. Relationship of coastal water convergence and Fraser River discharge to migration of Fraser River sockeye through Johnstone Strait, Pac. Biol. Sta., Nanaimo, B.C. Rept. 32-7.
    Predictive relationship between percentage of returning sockeye salmon passing between Vancouver Island and the mainland on their way to the river. Fraser River discharge and wind stress holding fresh water near the coast account for 70 percent of variability. Rain at time of spawn and hours of sunlight can account for 89 percent of variance in stock size off British Columbia from 1930-74 (personal communication to Lasker).
52. Williams, A. B. 1969. Penaeid shrimp catch and heat summation, an apparent relationship. F.A.O. Fish Rept. 57:643-656.
    Good shrimp fishery follows warm winters, and poor follows cold.
    Note: Cold of 1958 and 1976-77 were poor years. Relate to Johnson and McLain.

Matrix of Environmental Factors on Species
(Numbers refer to references in the Annotated Bibliography)

Species	Temperature	Temp trends	Temp extremes (incl. ice)	Salinity	Geostrophic currents	Ekman transport	Upwelling	Nutrients	Forage	Indicator org.	Meteorological phenomena	River discharge & precipitation
Anchovetta											23	
Anchovy							25		25			
Sardines				49							29	
Menhaden		46, 29				23, 31						
Herring	8, 14, 27		48					37	37		36, 5, 8	
Cod	47, 19, 28	10, 37				19					5, 41	
Pilchard	43	37						10, 37				
Haddock		7				36, 6					5, 6	
Hake											5	
Salmon	14	10, 29	23								36	51
Mackerel	27, 47	46, 29					23, 32		40		40	
Skipjack					23, 38							
Yellow tuna							4		4			
Albacore							26		26			
Butterfish		7										
Bluefish		44										
Weakfish		44										
Sole	20		24		20	20					20	20
Plaice		7	1, 9								41	
Yellowtail flounder	29, 42	7, 46										
General (fish)	2	29									29	
Larvae	43	16, 17	24, 30								41, 30, 40	30
Soft clam		50, 29										
Oyster				29								29
Blue crab												33
Green crab		50, 29										
Bay scallop	11											
Dungeness crab	14					23	34					
Penaeid shrimp	11		52									18
N. lobster	11, 13, 15, 47	12, 46										

Working Group Reports

Questions That Might Be Addressed by the Panels of the Fisheries Environmental Forecasting Workshop

1. This workshop has been predicated on the assumption that there exists a direct relationship between environmental variations and variations in fisheries abundance, and if we were bright enough or could observe well enough, we could delineate these relationships. A contrary hypothesis should be investigated which goes as follows: The variations in fisheries abundance are determined by environmental parameters which are on too small a scale, either spatially or temporally, to "observe" in the usual way in which physical oceanographers, meteorologists, climatologists, think of environmental observation and forecasting. In essence, what the contrary hypothesis suggests is that the critical environmental parameters as they affect reproduction and/or larval recruitment are within the noise level of our ability to observe and are not subject to prediction in any sense that is useful for fisheries managers.

2. It is economically feasible to relate environmental variation to fisheries variation, assuming that the critical relationships could indeed be observed. For example, it may be more cost-effective to ignore the environmental variation affecting larval recruitment and let the fish themselves be "environmental integrators." For example, it is sufficient to know that there has been a large year class of cod which will enter the fishery 3 or 4 years hence without having to determine the reason for that large year class. On the other hand, there may be "fish," such as shrimp, that enter the commercial fishery within a very short time after spawning, and in these cases it may be cost-effective to attempt to understand the relationship between fisheries abundance and environmental parameters.

3. Is our knowledge of either fisheries or environmental models sufficiently good to make us able to design so-called critical experiments to test hypotheses linking fisheries models and circulation? If not, what are the critical gaps in our understanding?

4. Can we identify and elucidate as an important research effort a category of critical-point problems (i.e., critical environmental conditions which produce a "flip" or catastrophic change in the system) amenable to quantification and early assessment? Examples: anoxia, 1976; Chesapeake runoff, 1972; el Niño; extreme yield variations.

5. To what extent can oceanic events in the Pacific be used to predict or explain coastal conditions along the western Atlantic?

6. What biological processes have the greatest potential for elucidating cause-effect relationships between climatic factors and fish production?

7. What research strategy is most likely to establish causal relationships between meteorological and oceanographic factors controlling secondary production (emphasis on larval fish survival), which is the process which perhaps holds the greatest promise for achieving understanding and long-term predictive capability for fishery resources?

8. What is the magnitude of, what are the patterns of, and what is the cause of interannual

variations in the circulation of the extended jurisdiction zone off the northeast United States? How do these circulation variations relate to fish abundance variations? Are there some simple environmental indices for fish abundance variations which are consistent with causal linkages (e.g., surface Ekman transport) between environmental factors and fish abundance?

9. Are there certain parts of the physical system, e.g., the shelf break frontal zone, where environmental factors are especially significant for fish abundance? Are regional estuaries coupled biologically through physical transport processes? Are there certain climatic episodes during which anomalous transfers of biota occur, e.g., exchanges around Cape Hatteras between the Middle Atlantic and South Atlantic Bights?

10. Can the life history of several species of fish be described together with the (nominal) seasonal circulation and hydrographic regimes of their environs? If so, can the sensitivity of the abundance of these species to (nominal) interannual variations in circulation and hydrography be evaluated?

11. Can we identify some new environmental indices to relate to fisheries production based on data and phenomena of, say, 1960 to 1969? Can we then test these indices on the 1970s data and phenomena in order to recommend monitoring strategies for the 1980s?

Summary Responses to Questions

WORKING GROUP 1 REPORT

Richard T. Barber, Chairman
Merton Ingham, Rapporteur

1. Broad-spectrum, general optimism about climate/fisheries investigations is difficult to substantiate without resorting to the citation of specific studies. We should address ourselves to further investigation of those studies which have given us some success. The goal of these follow-on studies should be an understanding of the bio-environmental systems involved. Each of the studies should involve three necessary components: (a) a sound time-series base of environmental data; (b) a developing understanding of the life history and interspecies interactions; and (c) a sound time-series base of fishery data. The emphasis must be on an understanding of the linkage between the environmental and fisheries data. The follow-on studies could be conducted with reasonable expectations of success with the Pacific anchovy and albacore tuna, Atlantic menhaden, and herring, cod, and haddock on Georges Bank.

2. The effects of environmental variation on year-class strengths should be determined, instead of merely assuming that the biota will integrate these effects and that monitoring of recruitment will provide all the information necessary. Without the understanding of bio-environmental relationships, a great deal of predictive capability is lost, particularly when anomalous environmental conditions impact on the stocks months or years before the monitoring of recruitment can reveal the consequences.

3. Yes, our knowledge is adequate to design critical experiments to test hypotheses linking fisheries and circulation in several species, including anchovy, herring, and menhaden. Gaps in our knowledge usually fall within the realm of life history and predator/prey interactions. For example, an experiment to define the trajectories and behavior of menhaden larvae during their spawning period south of Cape Hatteras could be conducted. The experiment would involve current meter arrays, Lagrangian drifters, meteorological sensors, frequent larval sampling surveys. In the case of Pacific anchovy ecology, an effort to directly monitor species composition and abundance of phytoplankton and microzooplankton during the spawning season, simultaneously with oceanographic and meteorological parameters, should be mounted. Either of these experiments should be conducted for several seasons to insure against being misled by anomalous conditions in a single season. Also, an effort to develop quantitative models must accompany the field studies.

4. Yes, critical-point or catastrophic events can be elucidated for possible research and monitoring in order to develop predictive capability. In addition to the examples offered we should add anomalous winter conditions, such as those in 1976-77, which are aperiodic and extreme, but amenable to monitoring and prediction. In this

case, a set of alternative quasi-steady-state conditions appears to exist, which are triggered by detectable precursor conditions.

5. There is some demonstrated atmospheric teleconnection between Pacific and Atlantic, with regard to sea surface temperature changes resulting from changes in the wind field and continental air mass invasions in the coastal area. This, however, is related more properly to hemispheric or global changes.

6. The biological processes which have the greatest potential for elucidating cause-and-effect relationships with climatic factors are: (a) survival and growth of larval stages, and (b) predation.

7. The research strategy most likely to establish causal relationships and to hold promise for long-term predictive capability has the following elements: (a) maintenance of long-standing monitoring programs to continue time-series data sequences, both biological and environmental, and (b) concentration on research into the linkage between the biological and environmental data sets through studies of survival and development of critical life stages of the subject species. This research also must be conducted over a long-enough period to insure that conclusions aren't based on highly anomalous conditions.

8. Nobody presently knows the answer to these questions, but hypotheses should be developed through hindcasting studies. Then experiments should be developed to yield the answers.

9. The boundary layers are parts of the physical system where environmental factors are particularly significant, because they represent flux gates for nutrients, larvae, etc., where exchange rates can be determined. The boundary layers also include the inshore edge of the system and the estuary entrances. A critical experiment should be conducted to verify inferred estuarine dependence of offshore species.

There are climatic episodes which are manifested in range extensions of subtropical and subarctic species into the Atlantic shelf water ecosystem.

10. Yes. For example, the Pacific mackerel, sardine, anchovy, Dungeness crab, and Atlantic menhaden and blue crab.

11. Yes. Richardson number, mixing energy and density gradient strength measures are some which are new to fishery applications. Species composition of ichthyoplankton and their forage may depend heavily upon upper-level dynamics and turbulence, so parameters which describe this are needed for correlative studies.

WORKING GROUP 2 REPORT

Jerome Namias, Chairman
Herb Austin, Rapporteur

1. The group was optimistic about studying relationships between climate and fisheries. The group felt that previous studies and those currently underway have demonstrated the link between recruitment of several species and certain physical processes. The cost effectiveness and economic feasibility will improve with better sampling and increased effort.

2. Dr. Namias repeated his concern that the biologists must play an active role in the forthcoming United States Climate Program. This role should be mutually helpful to climatologists, oceanographers, and fishery scientists.

3. The group felt that knowledge generated by studies such as the CUEA anchoveta related effects will transfer to other fisheries. A critical study would be of the meteorological-oceanographic forcing of the recruitment process of the Georges Bank haddock. Such a study would also provide spin-off information on the frequency and intensity of extra-tropical storms. The sea herring fishery may be of more immediate and critical interest to management but is of sufficient complexity that it does not lend itself to climate scale studies at this time.

4. In general, we cannot currently identify with sufficient lead time the conditions that lead to many "catastrophic" events of biological significance. We can, however, identify several of the factors leading to an "el Niño" and to the anoxic conditions in the New York Bight (1976). The system that set up the anomalous water mass stratification in 1976 was also responsible for the reduced number of storms. Such systems are of such a time and space scale that they lend themselves to climate studies. A payoff to fisheries managers would be to allow them sufficient lead time to

make a decision on the quota of, for example, the surf clam. Knowing such conditions are imminent, they could choose to fish down the stock. When considering extreme yield variations (from changes in recruitment), it was pointed out that the size of the spawning stock is as responsible for extreme *absolute* fluctuations as the environment, with a larger spawning stock producing a greater chance for *absolute* fluctuations. At smaller spawning stock sizes, however (while the *absolute* range of recruitment may be small, the *relative* fluctuations may be quite high), the effect of the environment is more important, as the variation in recruitment could cause a recruitment failure. With long-term good or bad environmental conditions, the relationship between stock and recruitment will change, with a greater maximum recruitment level produced under ideal conditions.

5. Because fishery stocks along and off the East Coast are dependent on oceanic and atmospheric variations there, it is important to note that sea-air interaction over the North Pacific Ocean, through atmospheric teleconnections, can influence western Atlantic atmospheric and oceanic currents and oceanic thermal and salinity structures. Thus, there are linkages between fisheries over (distant?) areas of the globe. A dramatic example is given by the contrast between the East Coast weather regime of the winters of 1975-1976 and 1976-1977, the former characterized by little East Coast cyclonic activity and the latter by frequent and intense cyclonic activity. The differing effects of these two winters are manifest in many fisheries variations (e.g., the anoxic conditions in the New York Bight of 1976, and the extensive cold weather fish kills during January and February 1977). One is referred to the paper by Johnson and McLain, 1975, cited in the "Annotated Bibliography" of Austin and Ingham. The NMFS Ship of Opportunity Program can give a good long-term picture of Pacific thermal structure and should prove useful as a monitoring mechanism.

6. Several biological processes have a great potential for elucidating causal environmental/biotic relationships. The recruitment process is dependent upon larval mortality, which is composed of a complex series of components. Reuben Lasker's talk demonstrated one such component of the mortality problem. We feel that larval mortality is a primary biological process affecting recruitment.

7. One proposal for research strategy is to conduct a series of multidisciplinary skull sessions followed by the formation of a multidisciplinary task force which is physically collocated in the same building. This task force would conduct historical and current data analyses prior to initiating empirical analyses. These analyses would be precursors of the development of conceptual understanding, and ultimately to quantitative computations and predictions on time scales ranging from days to months, seasons, years, or decades.

8. An answer to this question will require years of study. We recommend a monitoring program that provides data on the what, where, and how often of causal events and fisheries fluctuations. The wind system indices developed at PEG/NMFS for Ekman transport and upwelling have proven their effectiveness when used as the causal parameter (or process). Other indices could be developed for thermal anomalies (similar to heating degree days), river discharge (precipitation index), or heat fluxes.

9. There are physical systems of particular significance to fisheries, although those of significance to recruitment processes are more limited. The area of the shelf break is the most dynamic region but is of less importance to recruitment of commercially significant species. The same is true for the Hatteras barrier. Of greatest significance are the shelf transport mechanisms.

10. In general, the *fate* (as opposed to life histories) of a stock is not considered relative to seasonal variations. Abundance is not a sensitive factor; migration, on the other hand, is. The ecosystem can be defined, with its annual and interannual fluctuations.

11. As in question 8, there are new indices that are needed. Each should represent a process. Examples are: heat fluxes (incl. Δ T), thermal anomalies, precipitation (local or snow), transport.

WORKING GROUP 3 REPORT

Frank Williams, Chairman
Chris Mooers, Rapporteur

1. Fisheries predictions are made in a variety of ways. Predictions of year-class strength are the most common, and are made for estimates of OY*

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*OY – *optimum yield.*

and management of the resource. Predictions of timing of migrations or distributions are made for improving fishing strategy. Predictions of anomalies of environmental variables or of indices of environmental processes are made for estimating larval survival, recruitment, abundance, and/or availability.

2. Some fisheries are supported by many year classes, some by few. This property influences their presumably different responses or sensitivity to climatic variations.

3. Steps to improve the predictability of environmental influence on fisheries would include:

(a) formulation of species' specific research problems;

(b) incorporation of dynamical relationships in monitoring indices (the so-called upwelling index, for instance, which is based on the offshore Ekman transport concept, has been useful); there may emerge additional concepts with utility for monitoring the environment as related to its role in fisheries;

(c) collocation of fisheries and oceanographic studies in continental shelf, near-shore, and estuarine areas;

(d) coordination of basic research and applications studies;

(e) the fostering of interdisciplinary research through production of a favorable funding environment for the requisite interactions;

(f) pursuit of (e) might lead to the formation of interdisciplinary teams;

(g) the generation of long-time series for such quantities as the position and strength of oceanic gyres and the Loop Current.

4. There exists a number of examples of climatic influences on fisheries (synergistic contribution of fisheries and environmental effects), such as:

(a) the el Niño and the Peruvian anchovy;

(b) the distribution of the albacore tuna in relation to the North Pacific Transition Zone (subtropical front); and

(c) the onshore movement of menhaden larvae in the vicinity of Cape Hatteras and Ekman transport.

5. On the East Coast, lack of satisfactory communications between oceanographic and fishery scientists, both basic and applied, and governmental and nongovernmental, continues to hinder the development of predictive knowledge for the role of climate in fisheries. A promising partial solution could be the establishment of an annual forum (informal conference) similar to the Tuna/EPOC Conferences on the West Coast.

6. The impact of extreme environmental events and chronic conditions on fisheries needs to be carefully documented. One reason for this is to avoid false alarms or diagnoses which can damage the credibility of the operational fisheries and oceanographic communities. It can be anticipated that there will be an increasing need to distinguish possible fisheries-induced, anthropogenic, and natural causes of anomalous conditions in fish stocks.

7. The "climate and fisheries problem" includes the effect of climate on:

(a) larvae;

(b) distribution of juveniles and adults;

(c) abundance and availability of juveniles and adults;

(d) the response to relatively long-term (ca. 25 yrs.) climatic variations by populations of long-lived fish;

(e) biological processes, such as tolerance, growth, competition, predation, distribution, energetics, behavior; and

(f) response to gradients and rates of change in temperature and other such variables, which are probably more important than the values of the variables themselves.

To the extent that larval survival is crucial to recruitment, the fact that larval stages last for days to months suggests that year-class strength may be very sensitive to subtle and relatively small variations in the phase of environmental cycles.

WORKING GROUP 4 REPORT

Michael Sissenwine, Chairman
Eugene Rasmusson, Rapporteur

We have entered a period when interest in certain programs, e.g., climate and advances in observational systems, are resulting in significant increases in the acquisition of marine physical data. These improvements in the physical data situation are being matched by enhanced gathering of biological data, both in terms of quality and quantity. A corresponding effort should be undertaken in the structuring of models, which could be used as a guide to assure the collection of the most useful data.

The central question to be addressed is: What determines that a year class will be good or bad, and how can this be predicted? The uses of this type of information fall into two broad classes: (a) short-term management, and (b) broader, long-term policy decisions.

Consider first the short-term management problems. Current management practices seem to be adequate for long-lived species, which are readily surveyed. However, there are many examples of short-lived species which are difficult to survey, and for these, predictive relationships, including environmental effects, are important. Many of the stocks which have collapsed due to the effects of environment and overfishing fall into this class.

A reasonable cost-benefit case must be made for the inclusion of climatic effects in these models rather than to proceed as an article of faith. This may be an area for the use of theoretical models to aid our understanding and reasonably demonstrate the premise. Further demonstration may come from documented cases of fishery collapse which can be traced to environmental effects.

Research Strategy

There are probably a half-dozen stocks on each coast for which adequate information is available to allow the development of climate/fisheries relationships. We suggest that the following species offer the greatest prospect for progress:

(a) those species where year-class strength depends on favorable circulation for allowing early life stages to be transported to or retained on grounds favorable for survival; and

(b) those species where year-class strength is dependent on match/mismatch of productive cycles, which is a more difficult problem.

The use of past data which is readily available should be emphasized in the early stages of research rather than to immediately propose new monitoring efforts. This will often be sufficient to establish a detailed regional climatology from which to tie down the regional biological adaptations. The early stages of the data analysis should also concentrate on the description and understanding of the more extreme events in the historical record.

This should lead naturally to the design of a monitoring scheme. The question still arises as to what should be proposed at the present time in the way of enhanced monitoring, analyses, and indices which have a reasonable expectation of broad future use. We suggest the following:

(a) indices
  1) total heat storage in the mixed layer,
  2) long shore flow on each coast,
  3) predominant cyclone tracks,
  4) polar-front drift in the major ocean basins (already identified as an important element in ocean climate), and
  5) time series of temperature and wind from meteorological buoys and selected area XBTs.

(b) analyses
  a vigorous program should be undertaken to analyze the NMFS Ship of Opportunity data in order to provide input to other studies, and to determine the adequacy of the sampling program.

(c) enhanced monitoring
  a single cross-shelf section, possibly in connection with the monitoring of offshore drilling.

The strategy for approaching the match/mismatch problem involves:

(a) the determination of the makeup of plankton distribution during the spawning season as a function of factors such as the timing of the spring phytoplankton bloom, and

(b) the feeding habits of the larvae.

The establishment of critical conditions which lead to catastrophic effects on year-class strength can be determined for situations involving factors such as seasonal critical temperatures, unusual streamflow (even factors such as diversion of rivers), or circulation patterns. Relationships should be developed in anticipation of the availability of adequate long-range predictions of temperature and precipitation (streamflow) anomalies.

Up to now, we have discussed the single-species, immediate management problem. It would be useful to relate long-term climatic changes to shifts in species composition of the fish community. It may only be possible to approach the problem qualitatively at present. Complex ecosystem models have not yet adequately addressed the problem of modeling the arrival of early life stages of fish. High-intensity laboratory and field programs directed at a specific fish stock are probably needed in order to formulate specific hypotheses on the processes that determine year-class strength.

Research on the dynamics of the slope water also seems justified in attacking longer spatial scale, longer time scale problems. Applications of such studies include possibly relating the year-to-year variation in warm core eddies to the production of short fin squid populations and other migrating species that school on and off the shelf. Note that residence times are roughly 6 to 12 months for shelf water, 2 years for slope water, and 20 to 30 years for the warm, subtropical oceanic waters.

Research on long-term changes should also include the documentation of past environmental changes and corresponding changes in the range limit of species. This information will be valuable for use in long-term climate projections.

For most of these efforts, there appears to be sufficient divergence in individual regional problems to suggest that regional efforts rather than a total centralization of the effort may be the best approach to the solution of the problem.

Case Studies

A Description of the Northern Shrimp Fishery and Its Decline in Relation to Water Temperature

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Introduction

Pandalus borealis Kroyer, the northern shrimp, occurs in commercial concentrations in both the North Atlantic and the North Pacific. In the western North Atlantic, the Gulf of Maine represents the southernmost portion of its range.

There are two fisheries in the western Gulf of Maine for northern shrimp: (1) the inshore Maine winter fishery, prosecuted by small vessels on adult females carrying eggs, and (2) an offshore Massachusetts fishery during warmer months, prosecuted primarily by large draggers which harvest immature and mature males and transitional shrimp converting into females.

The Gulf of Maine northern shrimp fishery began in 1938, with catches increasing to 264 metric tons (582,000 lbs) by 1945. Catches declined drastically after 1945 until the period 1953 to 1957, when no shrimp at all were landed. This was the period of very warm water temperature, the warmest of this century, and apparently the shrimp abundance was reduced to a very low level by a temperature-related agent.

Catches began to increase again in the late 1950s as the water cooled, and during the next decade abundance and catch greatly increased, culminating in a total catch of 12,800 metric tons (28 million lbs) in 1969. Since that time, landings have declined drastically (Figure 1). Dow (1963, 1964, 1966) has proposed that sea temperature levels during the year of spawning determine the year-class strength of the progeny produced, and observed that poor spawning success has been associated with consistently high or fluctuating mean monthly surface temperatures, while high levels of production have been associated with years of minimal monthly temperature fluctuations and moderately low temperature levels. He has documented a highly significant negative correlation between landings and annual mean sea water temperature 4 years previously as measured at Maine's Marine Resources Laboratory at Boothbay Harbor, Maine. Inasmuch as water temperatures

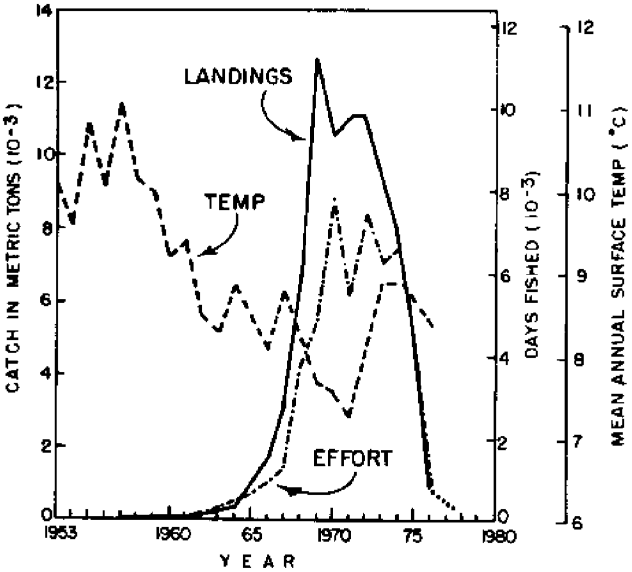

Figure 1. Landings of northern shrimp (1938-1976) plotted against annual mean sea surface temperature (measured at Boothbay Harbor, Maine) and effort. Temperature data are lagged by a period of four years.

have been higher than normal in the Gulf of Maine in recent years, the inference is that adverse temperature conditions could have contributed to present declines in stock abundance, although recent analyses suggest that high exploitation rates have been of equal or greater importance.

Temperature Effects

Apollonio and Dunton (1969) reported that high winter temperatures appeared to adversely affect embryonic development and suggested that the collapse of the fishery in the mid-1950s could have been caused by excessive egg mortality during high temperature years (1950 to 1953). Laboratory studies by Maine's Department of Marine Resources have indicated that eggs carried by shrimp develop very well up to temperatures of 10°C (50°F) (Alden Stickney, personal communication). Winter temperatures on the ocean bottom in the western Gulf of Maine during time of egg development are always colder than 10°C even in warm years. Water temperatures, therefore, in the range observed in the Gulf of Maine do not directly cause mortality of eggs.

Temperature does, however, have a pronounced effect on the incubation time of eggs. For example, at an average temperature of 6°C (43°F) the incubation period lasts about 120 days; at an average temperature of 4°C (39°F) incubation lasts about 147 days. This difference, which approximates the difference between a moderately warm and a moderately cold winter, could mean the hatching of eggs a month earlier following a warm winter. If larvae are produced before the spring bloom of plankton, they could find themselves without food.

Another possible cause of mortality associated with water temperature is a protozoan parasite that infects the eggs. If warm water enhances the survival of this parasite, and the parasite, in fact, kills large numbers of eggs, then this might be the direct causative agent of shrimp mortality associated with water temperature.

Assessment and Management

Landings, indices of abundance, instantaneous rates of fishing mortality, stock size, and recruitment estimates are given in Table 1.

Table 1. Landings, indices of abundance, calculated abundance, recruitment, and fishing mortality (F) estimates for the Gulf of Maine northern shrimp stock.

Year	*Landings (metric tons)*	*Commercial catch/day fished* (kilograms)*	*Catch/30 min. tow Maine research surveys (kilograms)*	*Abundance (thousand metric tons)*	*Recruitment (thousand metric tons)*	*Instantaneous fishing mortality (F)*
1958	2					
1959	7					
1960	41					
1961	31					
1962	176					
1963	254					
1964	423	962				
1965	949	1,352				
1966	1,766	1,887				
1967	3,171	2,549				
1968	6,610	1,855	56.9	15		.71
1969	12,824	2,790	31.2	27	22	.75
1970	10,647	1,556	40.8	24	14	.71
1971	11,130	2,263	9.4	14	5	1.95
1972	11,095	1,746	6.9	15	14	1.72
1973	9,405	1,787	9.0	18	15	.88
1974	7,986	1,433	4.5	10	4	1.95
1975	5,298	1,383	8.1	8	7	—
1976	1,066	857	5.4	5		.89
1977				3		
1978				1		

**Combined vessel classes 0-50 GRT and 51-150 GRT.*

Instantaneous total mortality coefficients (Z) were calculated from catch-curve analyses, and an assumed rate of natural mortality (M = 0.25) was subtracted to estimate F.

Stock-size estimates were obtained by calculating exploitation rates from estimates of F and relating them to catch. Recruitment estimates were obtained by subtracting the survivors in a given year from the estimated stock size in the year immediately following. The indices of abundance as well as the calculated abundance, recruitment, and landings all decreased after 1972. Estimates of F were extremely high for 1971, 1972, and 1974.

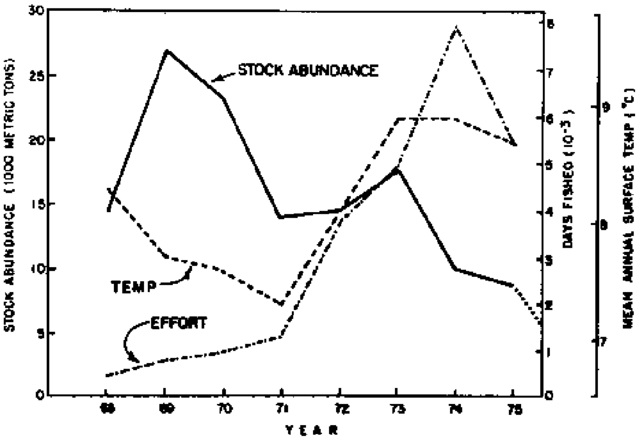

Figure 2. Trends in stock size (1968-1975) compared to trends in temperature (sea surface at Boothbay Harbor, Maine) and effort (both lagged 4 years).

Figure 2 shows the relation between temperature, effort, and stock-size estimates for the period 1968 to 1975 (effort and temperature lagged 4 years). We have chosen to lag effort by 4 years under the assumption that fishing mortality on egg-bearing females would directly affect subsequent recruitment. From 1968 to 1971 (lagged 4 years), the mean annual temperature was declining, yet the stock abundance also declined. Effort data increased from 1964 to 1967 (affecting stock size from 1968 to 1971). Landings increased in proportion to effort, but recruitment and stock size 4 years later declined, even though water temperatures were not only favorable but at their lowest in 1967 (lagged 4 years in Figure 2 to reflect impact in 1971). Both water temperature and effort increased in 1968 and 1969 (1972 and 1973 lagged), but water temperature remained constant in 1969 and 1970 (1973 and 1974 lagged), while effort increased by 60 percent and stock abundance declined by 44 percent. So while it is known that warm sea water temperatures are detrimental to shrimp production, the effect of increasing water temperatures in the early 1970s is difficult to quantify in view of the increase in fishing effort.

The northern shrimp resource has been managed under the Atlantic States Marine Fisheries Commission by the Northern Shrimp Sub-Board (of the State-Federal Fisheries Management Board) which acts on recommendations from the Northern Shrimp Scientific Committee. Most of the assessment described in this paper was done by this committee, although the authors were responsible for the original assessment. Management efforts began in 1973 with the imposition of interim mesh regulations. Stronger mesh-size restrictions were imposed in September of 1975, and the first closed period of fishing was July 5 to September 27, 1975. On April 15, 1976, the shrimp fishery was closed until the present (spring of 1978), except for January 1 to May 15, 1977, when a total allowable catch of 1,600 metric tons was allowed.

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The Relationship Between Temperature and Production of the Southern New England Yellowtail Flounder Fishery

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More than 600,000 tons (metric) of yellowtail flounder *(Limanda ferruginea)* valued at over 120 million dollars have been landed in southern New England and New York since the onset of fishing in the late 1930s. There are 3 fishing grounds on which yellowtail flounder are primarily sought by United States fishermen (Royce et al., 1959). These are the southern New England ground (Nantucket Shoals to Montauk Point), the Cape Cod ground (eastern shore of Cape Cod and Massachusetts Bay), and the Georges Bank ground. The southern New England ground has historically been the most productive, although in recent years its yield has been exceeded by the yield of the Cape Cod and Georges Bank grounds.

Prior to 1935, yellowtail flounder on the southern New England ground were unexploited. The fishery developed rapidly, yielding about 29,000 tons in 1942. It then steadily declined to a low of 1,500 tons in 1954 before rising to around 20,000 tons annually through most of the 1960s, with a peak of more than 30,000 tons in 1969. The yield once again declined steadily during the 1970s (to date), producing about 2,000 tons in the most recent years. Much of the variability in yield reflects variability in fishing effort, but a threefold variation in catch per standard day of fishing (which should be proportional to stock size) also has occurred. Royce et al. (1959) reported that the decline during the 1940s and 1950s was not accompanied by the normal symptoms of overfishing: a declining average size, an increasing proportion of young fish, or an increasing growth rate. Therefore, it was particularly appropriate to consider the influence of environmental conditions on production of this stock. The decline of the fishery during the 1970s followed a tremendous increase in fishing effort, particularly by non-United States fleets during the late 1960s. Therefore, it is likely that excessive fishing pressure played an important role in the decline during the 1970s, but environmental conditions probably also contributed to the decline.

Royce et al. (1959) first suggested a relationship between the southern New England yellowtail flounder fishery and temperature. He suggested that a warming trend may have effected a temporary northeastward shift in the population center. Lux (1964) went on to correlate relative abundance (catch per standard day fishing) with surface water temperature at Boothbay Harbor, Maine. There was a statistically significant (at the 5 percent level) inverse correlation, but because of the inadequacy of the available time series of temperature data, which resulted in considerable unexplained variability in relative abundance, he concluded that the relationship was of little use.

Sissenwine (1974) investigated the relationship between temperature and production by the southern New England yellowtail flounder population, instead of between temperature and catch per standard day of fishing.

Estimates of annual recruitment and surplus production by the stock for the period 1944 to 1965 were derived. A strong inverse correlation (correlation coefficient of about 0.90) between air temperature at Block Island, Rhode Island (on the edge of the southern New England ground), and recruitment and surplus production was found. In order to increase confidence in this correlation, the available data were randomly divided in half and regression models were fit to each half of the data separately. The coefficients of the models from each half were then compared and found not to be significantly different from each other. This procedure corresponds to fitting the model to one half the data and testing it against the other half. In addition, the residuals of the model were inspected to assure that they were not autocorrelated and that their variance was stable.

The Block Island air temperature record was used because it is the only available temperature record over an appropriate time period collected in a standardized fashion within reasonable proximity to the fishing ground. There is precedent in the literature for using air temperature data as a substitute for nonexistent water temperature data, particularly when average conditions over a year or more are considered (see Sissenwine, 1977). Also, the temperature at Block Island is correlated with the bottom water temperature at Lurcher Lightship off Nova Scotia and the surface water temperature at Woods Hole, Massachusetts, for example. Furthermore, the relationship between temperature and production is probably indirect, resulting from a complex set of interactions between species (perhaps a match/mismatch situation). Thus, any temperature record (air, surface water, or bottom water) is only as meaningful as its ability to serve as an independent variable in a prediction model. The Block Island air temperature appears useful in this role.

Simple regression models relating the effect of the environment on fish production do not provide an adequate framework for considering the joint effect of the environment and of fishing on a population. Therefore, a compartmentalized simulation model of the fishery was developed (Sissenwine, 1977). The population was divided into 10 age groups, each of which was subdivided into 7 size categories. The model simulated discard mortality as well as fishing mortality. Fishing and discard mortality rates depended on the level of fishing effort and gear and market selection factors. Seasonal variations in growth and exploitation rate were incorporated into the model. A linear relationship between recruitment and egg production and a von Bertalanffy growth function was assumed under average environmental conditions. The actual recruitment and growth rates during each year were estimated by applying an adjustment corresponding to observed anomalies in temperature. The model accounted for 85.5 percent of the variability in yield of the fishery from 1943 to 1965 and appears to adequately simulate the fishery during the period 1966 to 1972, although none of the data from the latter period was used to estimate the model parameters (Figure 1). Since 1972, the fishery has continued to produce only a low yield. Although the model has not actually been run for these more recent years, the recent trends in temperature and fishing effort are such that a low yield would certainly be predicted by the model.

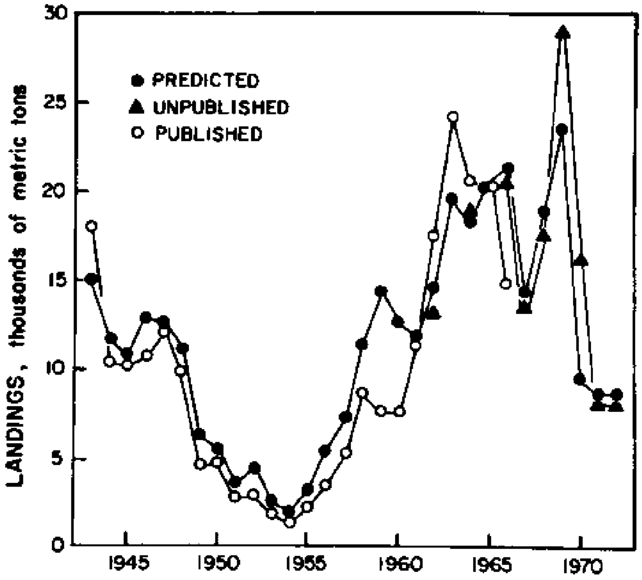

Figure 1. Results of simulation of the southern New England yellowtail flounder fishery and corresponding reported annual catches (Sissenwine, 1977).

Unfortunately, the model described above incorporates the effect of temperature empirically. The mechanisms by which temperature either directly or, more likely, indirectly affects production is unknown. Nevertheless, the model does appear to have predictive ability. Currently, the stock assessments that serve as a biological basis for management decisions depend heavily on prerecruit indices which allow prediction of the productivity of the population after the biological system has integrated most of the impact of environmental anomalies. Thus, from a practical standpoint, the assessment method now in use is probably adequate for management without explicit consideration of environmental factors.

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A Larval Transport Mechanism for Atlantic Menhaden*

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A study was undertaken in 1972 to 1974 to determine the influence of environmental factors on year-class strength of Atlantic menhaden *(Brevoortia tyrannus)*. Since year-class size is a function of the size of the spawning stock and of the effects of the environment, it was necessary to determine both the density-dependent and the density-independent relationships in order to weigh the relative influence of each.

Menhaden spawn along most of the United States East Coast, primarily north of Cape Hatteras in the summer and fall and south of Cape Hatteras in the winter. Most spawning, particularly south of Cape Hatteras, occurs well offshore. The species is estuarine-dependent, and larvae enter estuaries after an offshore phase lasting 1½ to 2 months.

A mechanism for the transport of larvae from offshore spawning areas to inshore nursery grounds during the passive drift phase would increase the survival rate of Atlantic menhaden. Theoretical wind-driven water mass movement (Ekman transport) was reviewed for its potential as a transport mechanism. Net water movement was found to be onshore during winter months both north and south of Cape Hatteras and to vary extensively from year to year. Peak periods of onshore transport coincided well with periods of menhaden spawning activities (Figure 1).

An intensive larval sampling program was carried out in Onslow Bay, North Carolina, from October 1972 through April 1974. The purpose of the survey was to determine the timing of spawning in Onslow Bay, the distribution and abundance of larvae as related to oceanographic conditions, and the relationship between oceanographic and biological findings and theoretical Ekman transport. Differences in distribution and abundance during the winters appeared related to different oceanographic conditions. During the first winter, massive intrusions of colder, low-salinity water entered Onslow Bay from the north, carrying larvae spawned north of Cape Lookout.

During the second winter, oceanic water was found in Onslow Bay and there was strong evidence of water mass movement offshore. Circulation patterns during the two winters corresponded with expected circulation determined from atmospheric pressure gradients which generate wind-driven circulation. A real relationship between theoretical Ekman transport and larval movement was apparent, supporting the hypothesis that Ekman transport acts to carry larvae from offshore spawning grounds to inshore nursery areas.

A spawner-recruit function was derived for Atlantic menhaden and used as a basis for determining the density-independent environment influence. The yearly observed number of fish recruited at age 1 was divided by the number of fish estimated from the spawner-recruit curve to determine the survival index for each year class from 1955 to 1970. An index greater than 1.0 indicated higher than expected survival and was attributed to environmental factors conducive to good survival.

**Partially abstracted from Nelson, Walter R., Merton C. Ingham, and William E. Schaaf. 1977. Larval transport and year-class strength of Atlantic menhaden. U.S. Nat. Mar. Fish. Ser. Fish. Bull. Vol. 75 (1). pp. 23-44.*

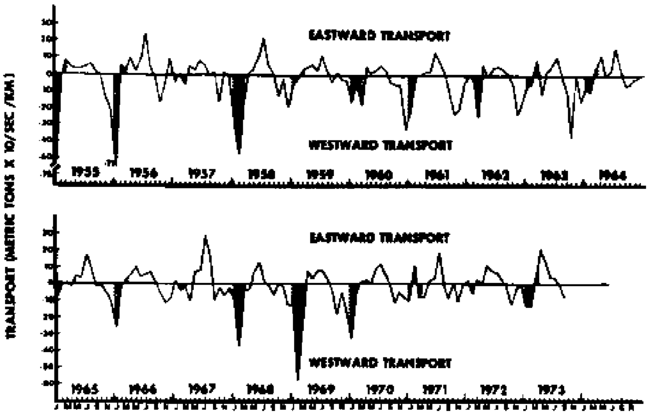

Figure 1. Monthly average zonal Ekman transport at Lat. 35°N, Long. 75°W, 1955-1973. January-March spawning period is shaded.

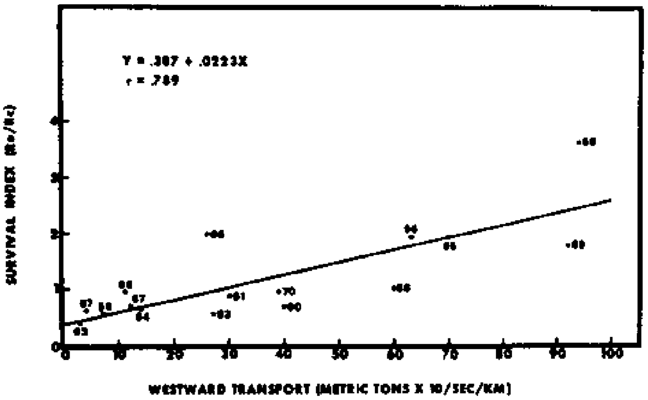

Figure 2. Linear regression of calculated survival index (observed recruits/calculated recruits) for Atlantic menhaden on sum of January-March zonal Ekman transport at Lat. 35°N, Long. 75°W, 1955-1970.

Individual regressions of the survival index on the various environmental factors were run. Zonal Ekman transport at 35°N, 75°W accounted for over 62 percent of the variance between actual and expected recruitment for Atlantic menhaden and had a correlation coefficient of 0.789 with the survival index (Figure 2). Another transport index at 33°N, 78°W also was highly significant, leading to the conclusion that transport south of Cape Hatteras is a major factor in the formation of year-class size. Transport north of Cape Hatteras in the Middle Atlantic Bight at 39°N, 75°W was also significant through the late fall and winter, indicating that the process is important along most of the menhaden spawning range.

A range of recruitment levels, based on years of high and low transport, was developed for Atlantic menhaden and indicates a wide range in numbers of recruits that can be expected under similar stock sizes at various transport rates. A chronological representation of the spawner-recruit relationship for Atlantic menhaden shows three different regimes in the 1955 to 1970 period. Stock size was high in the late 1950s, and usually exceeded that necessary to produce the maximum number of recruits. Heavy fishing pressure and poor survival resulted in a period of decline in stock size from 1961 to 1966. The stocks then reestablished around a small stock level which is too low to allow large-scale response to favorable environmental conditions.

Based on the determination of density-dependent and density-independent stock and recruitment functions for Atlantic menhaden, basic conclusions are: in years of poor environmental conditions, recruitment is low regardless of stock size; extremely low spawning stock sizes in years of poor environmental conditions result in recruitment below the level needed to maintain the fishery; favorable environmental years will produce exceptional year classes and a proportionally greater harvestable surplus at stock sizes near the spawning optimum; and a series of poor environmental years, coupled with excessive fishing pressure, will reduce stock size to a level which produces little harvestable surplus.

The Effect of Weather and Other Environmental Variables upon Larval Fish Survival Leading to Recruitment of the Northern Anchovy

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Recent work in the California Current on the effect of weather and other environmental variables upon larval fish survival leading to recruitment of the northern anchovy (Lasker, 1975, 1978) presents us with evidence which clearly shows that in some cases upwelling (Figure 1), while effective in enriching the upper layers of the sea for phytoplankton production, could also be detrimental to larval fish survival because of great dilution of larval fish food organisms and the subsequent replacement of these with diatoms which cannot be fed upon by first-feeding larval anchovy (Figures 2 and 3). Storms also can be detrimental by preventing stratification of potential larval food organisms (Figure 4). The mechanism of dilution keeps the concentration of larval fish food organisms below a threshold needed for supplying the metabolic and growth needs of anchovy larvae.

It has been suggested that the same procedures used for predicting wheat yields in Russia by using climate data bases could be used in fishery predictions. This premise is challenged, for the life history of the anchovy illustrates that the correlation between weather and recruitment cannot be a simple one. Rather, it must take into consideration nuances of the larval life history that are not necessarily consistent from year to year because of biotic and abiotic changes in the environment.

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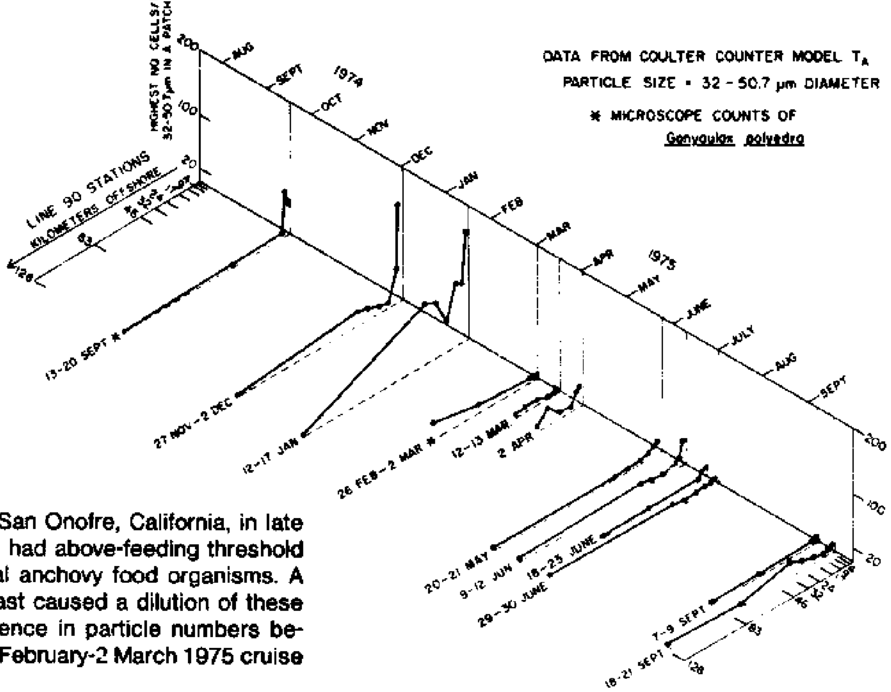


Figure 2. The inshore zone off San Onofre, California, in late 1974 and through January 1975 had above-feeding threshold concentrations of potential larval anchovy food organisms. A massive upwelling along the coast caused a dilution of these food organisms. Note the difference in particle numbers between the 12-17 January and 26 February-2 March 1975 cruise (Lasker, 1978).

A

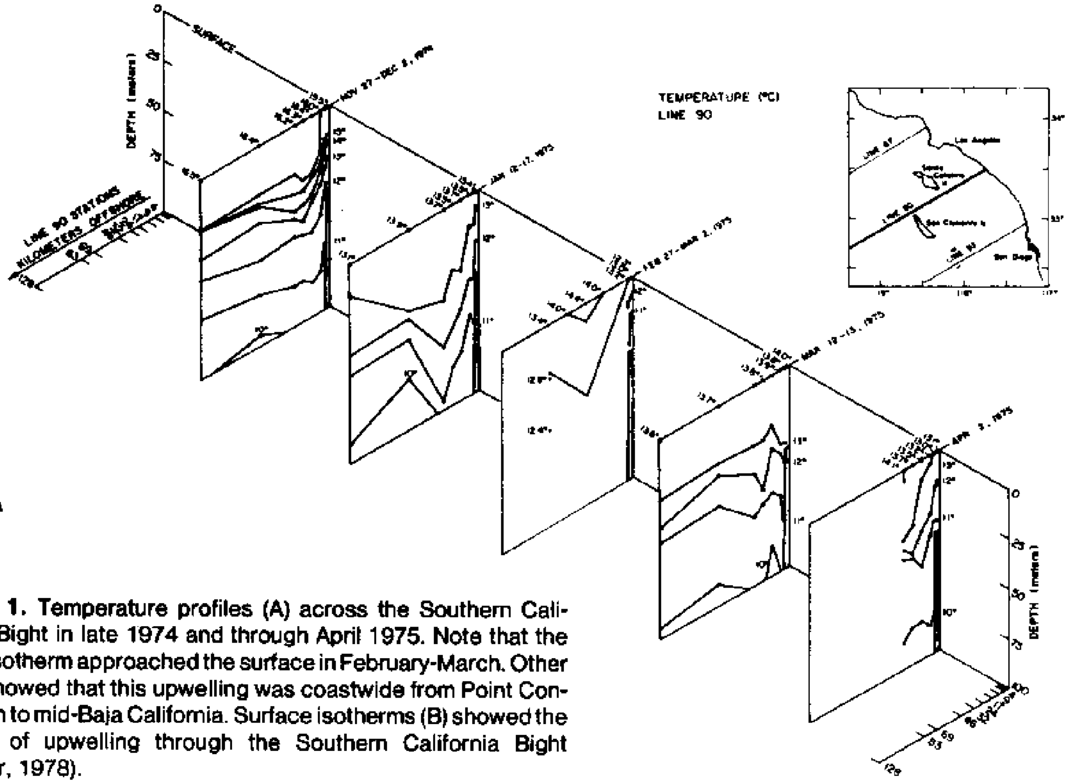
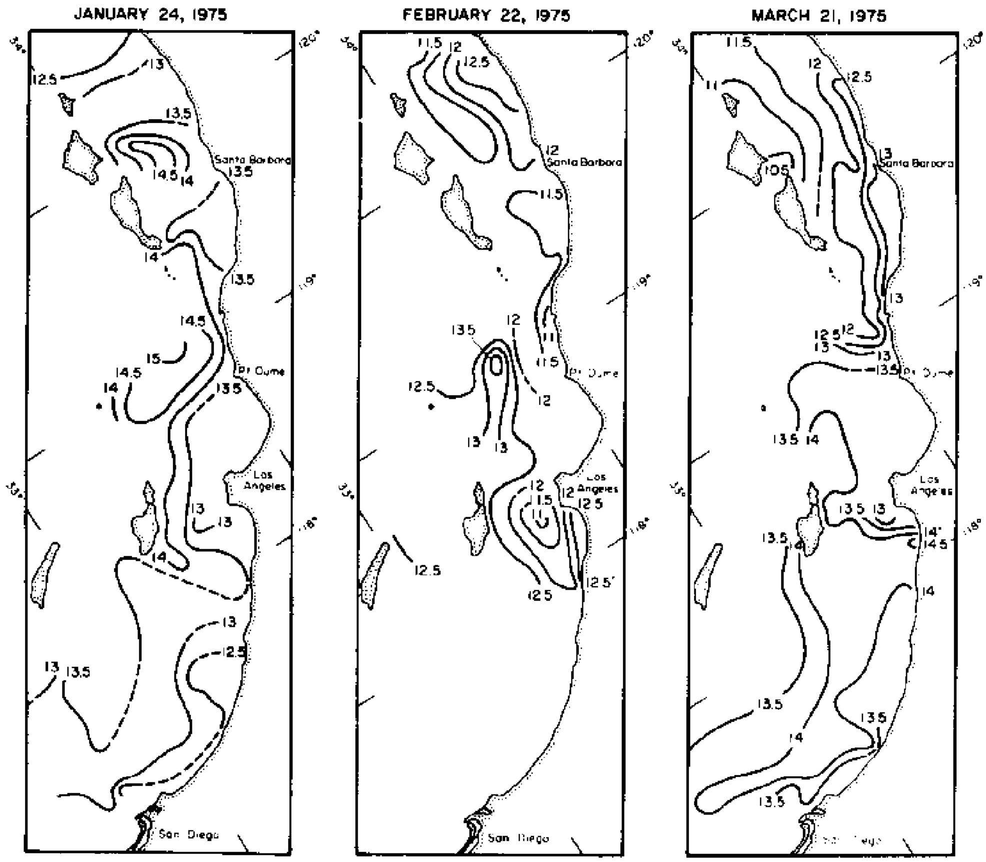


Figure 1. Temperature profiles (A) across the Southern California Bight in late 1974 and through April 1975. Note that the 11°C isotherm approached the surface in February-March. Other data showed that this upwelling was coastwide from Point Conception to mid-Baja California. Surface isotherms (B) showed the extent of upwelling through the Southern California Bight (Lasker, 1978).

B



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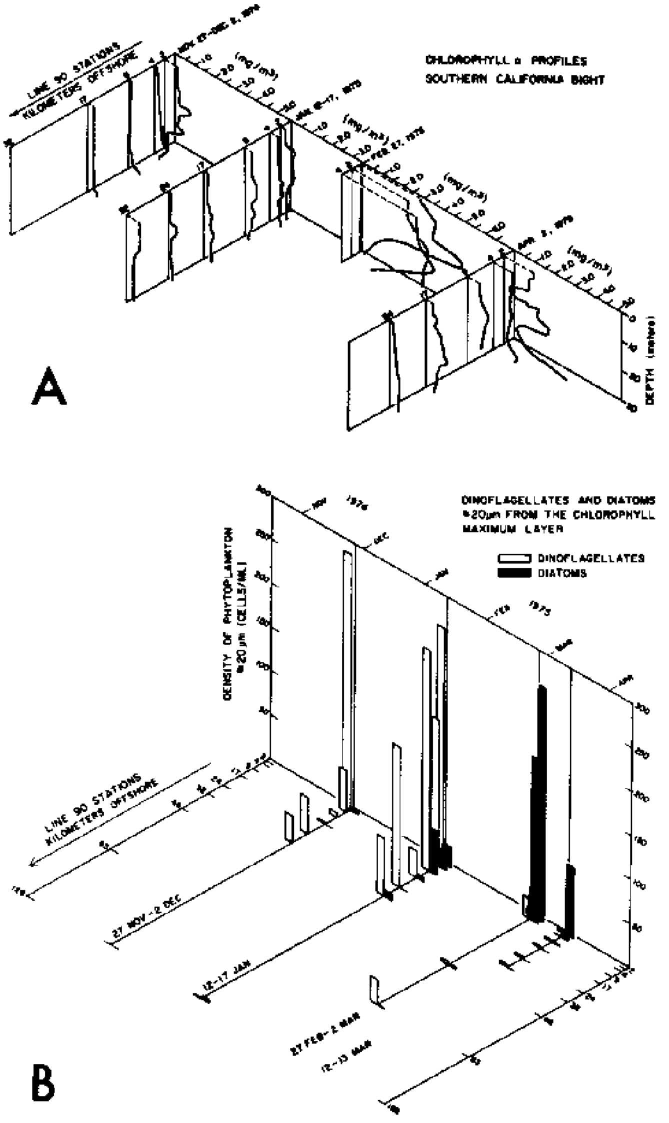

Figure 3. The upwelling shown in Figure 1 resulted in high productivity of diatoms. However, diatoms, unlike dinoflagellates, are not eaten by first-feeding anchovy larvae and do not contribute to their survival. (A) chlorophyll profiles, (B) diatoms replaced dinoflagellates (Lasker, 1978).

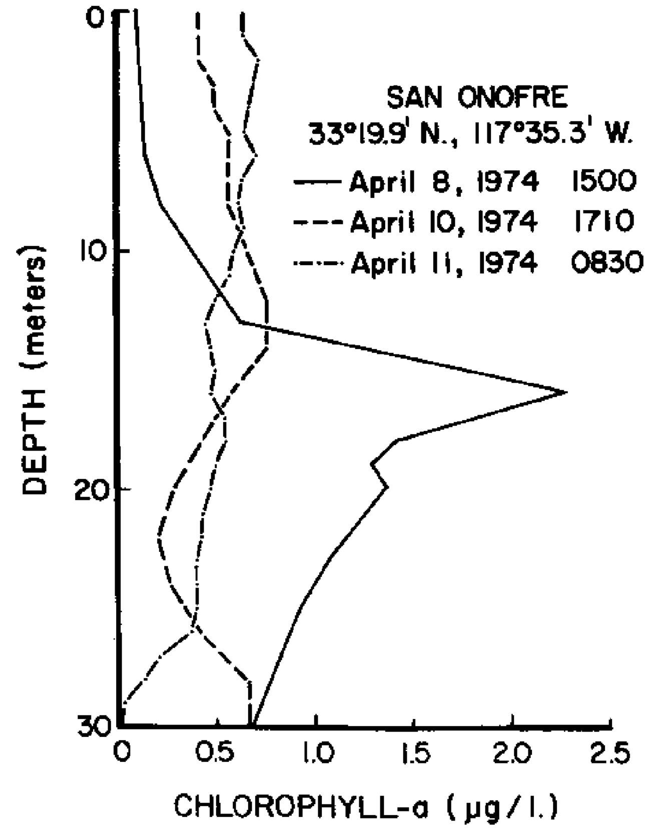

Figure 4. Induced turbulent mixing by storms are also effective in lowering threshold concentrations of larval anchovy food aggregations. In this figure, chlorophyll profiles are shown which were taken the day before and two successive days after a violent wind storm in the Southern California Bight off San Onofre, California. Reduction in chlorophyll indicated the extent of turbulent mixing (Lasker, 1975).

Climatic Variation and the Pacific Mackerel Fishery

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The Pacific mackerel fishery, a companion fishery to the Pacific sardine fishery, has shown a developmental pattern which is becoming all too common among fisheries for small pelagic species. In Pacific mackerel the explosive expansion of the fishery occurred in the mid 1930s, and the subsequent erratic decline to near commercial extinction was completed by the late 1960s (Figure 1). A cohort analysis (1928-68), using a natural mortality rate of M = 0.5, shows that the maximum total biomass occurred in 1933 (438,000 MT) and that the stock was reduced to less than half of one percent of the 1933 maximum by 1968 (1500 MT).

The exploitation rate increased as the stock declined (Figure 2), and the decline was often blamed on adverse climatic or environmental conditions, which is also typical in fisheries for small pelagic fishes. If the decline was associated with a climatic change, or other long-term environmental alteration, relative reproductive success would be expected to show a downward trend. However, there was no marked downward trend in recruits-per-spawner over the 1928-68 period. Reproductive success was markedly nonrandom. Runs of years with reproductive success alternate with runs of years with poor reproductive success (Figure 3). It is this combination, a series of years with below-average reproductive success and an increasing exploitation rate on the dwindling spawning stock, that has finished so many stocks of small pelagic fishes.

The observed record of spawning success in Pacific mackerel suggests that runs of years with poor reproductive success are common and we must expect them to occur in the future.

Recruitment in Pacific mackerel shows little density dependence. A Ricker spawner-recruit curve accounts for only 24 percent of the variance in recruitment. Climatic and density-dependent spawner-recruit models, developed with stepwise multiple regression and nonlinear regression

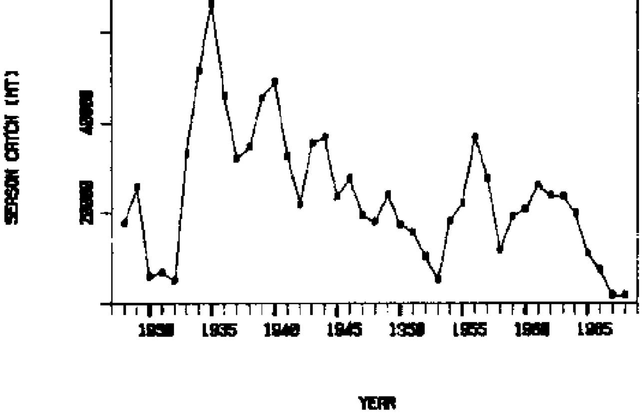

Figure 1. Relative spawning success (the natural log of recruit biomass per spawning biomass) and season catches from the 1928-1968 Pacific mackerel stock.

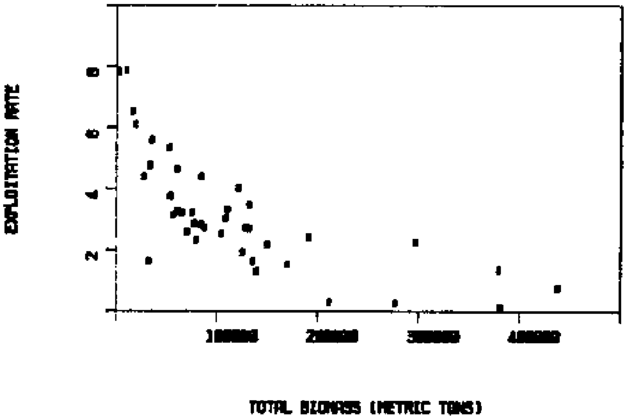

Figure 2. The relationship between the Pacific mackerel total biomass and its exploitation rate 1928-1967.

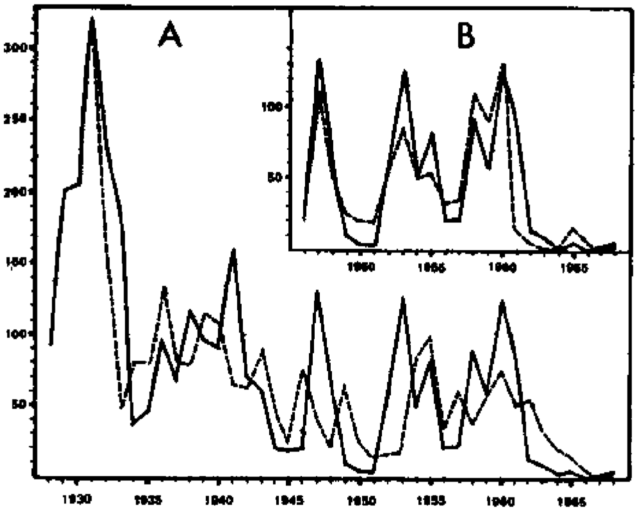

Figure 3. Observed and predicted recruitment of Pacific mackerel. (A) Ricker sea level model, (B) Ricker transport model.

procedures, were fitted to the data available for two time periods, 1931-68 (mostly shore-based data) and 1946-68 (which included more refined data on wind-driven circulation). The 1931-68 model accounted for 59 percent of the variation in recruitment; increased recruitment was associated with reduced sea level, reduced atmospheric pressure, and increased sea surface temperature during the spawning season. The 1946-68 model accounted for 76 percent of the variation in recruitment; increased recruitment was associated with increased coastal upwelling and decreased offshore convergence during the spawning season. Both models suggest that good reproductive success is closely associated with increased wind-induced upwelling just prior to and during the May to July spawning season (Figure 3).

Yield simulations of the Pacific mackerel stock show that maximum sustained yield (MSY) with a steady state dynamic pool model is above 41,000 metric tons. Simulations, incorporating the climatic and density-dependent spawner-recruit functions, predict that MSY cannot be attained when there is coherence in the recruitment fluctuations. Maximum long-term yield under the environmental conditions occurring between 1931-68 was only 25,000 metric tons.

The sharp decline in the 1960s, due to a long series of years with poor reproductive success (1962-67), and an increased exploitation rate, was associated with anomalously low upwelling indices during the spawning months in the Southern California-Northern Baja California spawning grounds. During the 1970s, wind-induced upwelling has increased, particularly in 1971, 1974, and 1976. The climatic- and density-dependent spawner-recruit models therefore predict good relative reproductive success in these years. The extremely low spawning biomass levels in 1971 coupled with the moratorium on the fishery in 1972 precluded any assessment of the 1971 reproductive success. In relation to the spawning stock size, the 1974 year class was very successful, and nearly the entire biomass in 1975 and 1976 were fish from the 1974 year class. Recent estimates of the 1976 year class indicate that the relative reproductive success was very close to the record 1953 year class, when there were 4.5 kg of recruits for each kg of spawners. The protection of the moratorium and the good reproductive success in 1974 and 1976 have allowed the stock to rebound, and present regulations will allow a limited fishery as the stock recovers. It is significant that the present regulations will decrease the exploitation rate when natural environmental variation produces the next set of poor reproductive years.

Upwelling Indices and the Oregon Dungeness Crab Fishery Catches

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Coastal upwelling occurs when the wind causes water to be transported offshore in the surface Ekman layer, resulting in an equal amount of water welling up to replace this water near the coast (see Sverdrup, 1938; Smith, 1968; or Knauss, 1978, pp. 120-125, for a discussion of the coastal upwelling process). Thus, the magnitude of the Ekman transport directed offshore, computed from the alongshore component of the wind stress divided by the Coriolis parameter, is an index of coastal upwelling.

Bakun (1973, 1975) computes coastal upwelling indices along the West Coast of North America using the atmospheric pressure fields prepared by the U.S. Navy Fleet Numerical Weather Control to obtain surface winds. In Figure 1 are shown the mean monthly offshore Ekman transport (in m^3sec^{-1} per m of coastline); these have been computed for 45°N, 125°W from 20 years of monthly mean atmospheric pressure fields (1948 to 1967) by Bakun (1973). These numbers are an index of coastal upwelling on the Oregon coast near 45°N. The upwelling season (the period of offshore Ekman transport and, hence, upwelling at the coast) runs from April to September; the mean Ekman transport over the season is about 0.4 m^3sec^{-1} per meter.

The wind and the weather differ from year to year—and so does the amount of upwelling of nutrient-rich water. Years with strong upwelling should be followed by good fishing years if upwelling does play a significant role in the ecology of coastal organisms. The reproductive success and survival of young animals should be enhanced by the abundance of phytoplankton in good upwelling years. Benthic species off Oregon (bottom fish, shrimp, etc.) must depend on the increased food availability during the summer upwelling for their growth and survival.

One delicious example is the Pacific Dungeness crab *(Cancer magister)* whose fishery shows large fluctuations in the yearly catch. Peterson (1973) showed that the catch of Dungeness crab during its fishing season (December through April) off Oregon is closely related to the amount of upwelling during the upwelling season a year and a half earlier. Figure 2 is a plot of crab catch off Oregon vs. Bakun's upwelling index. Notable is the weak upwelling period of 1960 to 1963 followed 1½ years later by poor crab catches in 1961-62

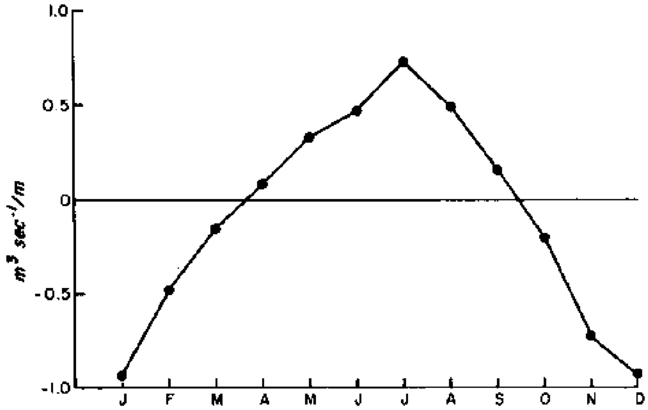

Figure 1. Average monthly upwelling indices at 45°N, 125°W (i.e., Ekman transport in m^3sec^{-1} per m of coastline) during 1948-1967. Positive numbers represent transport of coastal waters toward offshore and, hence, coastal upwelling; negative numbers represent onshore transport and conditions opposed to upwelling.

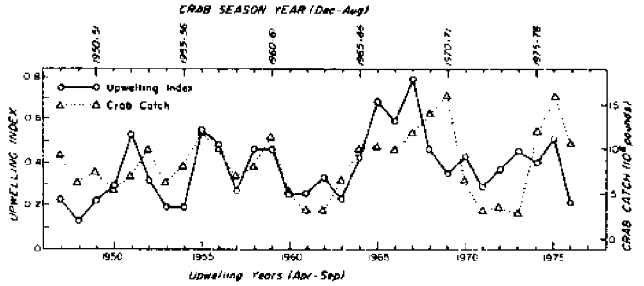

Figure 2. Crab catch off Oregon (in million pounds) and upwelling index (mean offshore Ekman transport at 45°N, 125°W for April through September in m^3sec^{-1} per m of coastline). Fishing effort data are not required, since virtually all legal-sized animals (i.e., 4½-year-old males; carapace width ≥ 6¼") are captured each year.

through 1964-65, and the high values of the upwelling index from 1964 to 1968 followed by near-record landings in 1965-66 through 1970-71. The large catch of 1970-71 would seem anomalous but very likely reflects the long-term effect that prolonged periods of very strong upwelling can have on the population.

Peterson (1973) hypothesized that the observed time lags were partially a direct result of slow energy transfer through the food chain. High standing crops of phytoplankton lag upwelling events by many days. Dramatic increases in zooplankton standing stocks lag the plants by one to two months (Peterson and Miller, 1975). The major link between pelagic and benthic food webs, copepod fecal pellets, will not fall to the sea floor in copious amounts perhaps until July. Increases in benthic populations will also lag in time. Therefore, benthic predators, such as the Dungeness crab, may not see increased food resources until the close of an upwelling season.

An additional component in the 1½-year lag occurs because of the timing of the annual molt. Older crabs shed their shells late in the upwelling season, from August through October. It is possible that this event takes place just before increased food levels are experienced. Since crabs must molt in order to grow, upwelling will not affect crab growth until the following year's molt. Good upwelling should result in good growth (= high molting success). Poor upwelling should result in both reduced survival and decreased molting success.

An alternate hypothesis has been offered by Botsford and Wickham (1975) to explain observed cyclic crab landings. Cross-correlations of crab landings and upwelling indices were significant at lags of 1½ and 2½ years. They suggest, however, that the relationship may not be causal. They feel that the cycles in crab abundance are caused by density-dependent recruitment. That is, during years of high adult abundance, survival of young crabs would be low because adults may be cannibalistic. When this weak year class reaches maturity 4 years later, cannibalism on younger crabs would then be low, thus creating a strong year class, and an 8- to 9-year abundance cycle.

Perhaps both the food availability and density-dependent hypotheses operate at separate times. During several-year periods of favorable upwelling, adult abundance and young crab survival would be high because preferred foods (clams, polychaete worms, and amphipods) are abundant. Adjacent years of weak upwelling would increase competition for food, reduce survival of all crab age classes, and force adults to feed on their young.

Further progress toward an understanding of the demonstrated relationship between upwelling and crab landings requires rigorous testing of the many hypotheses suggested above.

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The Control of Pelagic Fishery Resources in the Eastern Bering Sea*

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A Dynamic Numerical Marine Ecosystem model (DYNUMES III) which addresses interactions of major ecosystem components was used to study the dynamics of pelagic fish in the eastern Bering Sea, with emphasis on Pacific herring *(Clupea harengus pallasi)*, and to determine quantitatively the factors affecting relative abundances of stocks. The equilibrium biomass of herring in the eastern Bering Sea is 2.7 million tons, and the lower threshold value is 0.5 million tons (with density-dependent grazing on herring), below which recovery would be very slow indeed. The equilibrium biomass of other pelagic fish is 4.3 million tons.

The herring biomass has long- and short-term fluctuations which are induced and affected by several factors, such as environmental anomalies and interspecies interactions. There is, for example, an inverse relationship between walleye pollock *(Theragra chalcogramma)* and herring biomasses due to older pollock grazing on herring. Although the present state of the herring biomass in the eastern Bering Sea cannot be determined with greater accuracy due to the lack of proper data, it can be assumed to have been at a low level a few years ago due to the high abundance of pollock and is expected to be on the increase in recent years due to the decrease in the abundance of older pollock. The biomass turnover rate for herring is 0.5 and for other pelagic fish 0.95.

Herring abundance in the eastern Bering Sea is primarily affected by marine mammals, which annually consume roughly ten times more than the commercial catch. Herring abundance is also influenced by consumption by squids and other fish, and especially by water-temperature anomalies during winter and spring. Effects of the fluctuating offshore herring fishery has only a moderate effect on the equilibrium biomass of herring; the hierarchy of the influences on the herring biomass is given in this report in terms of defined "herring equivalences."

Pelagic fish constitute an important ecosystem internal food resource for other marine ecological groups in the eastern Bering Sea. The ecosystem internal consumption (and its possible year-to-year fluctuations) far exceeds the effects of the fishery and its variations on the state of the biomass of pelagic fish. Adult squids feed mainly on pelagic fish and exercise considerable influence on the magnitude and fluctuations of the pelagic fish biomass. Unfortunately, the squid biomass itself can only be estimated with a Bulk Biomass model, where emphasis is on the mean quantitative food composition of all ecosystem components.

The year-class strength in most pelagic species is largely determined by the ecosystem internal consumption in larval and especially in postlarval stages (and during the first two years of the life span), rather than by the number of spawners. Model results show that an increasing population expands in its spatial distribution and a declining population shrinks toward the center of its main abundance, the fringe populations disappearing first.

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The monthly source (growth exceeds consumption) and sink (consumption exceeds growth) areas for pelagic fish were found to be useful criteria in research and management problems. Temperature anomalies during the winter were found to affect considerably the sources and sinks of herring and other pelagic fish via physiological effects (food economy and growth). The growth rate of the biomass of a given species is a function of the distribution of its biomass with age and is affected especially by lower temperatures during the winter season. An 0.8°C temperature anomaly was found equivalent to about 11.3 thousand tons change of annual catch. Since the effect of a small temperature anomaly is relatively large in terms of possible increase of catch quotas, and since the anomaly would affect other commercial species as well, it seems to be imperative to monitor temperature anomalies at least during the winter and spring seasons in the eastern Bering Sea for optimum management of the fishery there.

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