PROBES

a prospectus on

PROCESSES AND RESOURCES OF THE BERING SEA SHELF

1975-1985

DELIBERATIONS OF A WORKSHOP IN
PROMOTION OF THE
U. S. PROGRAM FOR BERING SEA OCEANOGRAPHY
24-30 NOVEMBER 1973

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suggestions for a U. S. program

in Bering Sea oceanography ...

PROBES : a prospectus on

Processes and Resources of the Bering Sea Shelf 1975 - 1985

Deliberations of a workshop

held at Salishan Lodge, Oregon,

under the auspices of the

Office of Polar Programs

National Science Foundation

24-30 November 1973

D. W. HOOD, Convener

Institute of Marine Science

University of Alaska: Fairbanks

acknowledgments

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Members of the study group were selected on the basis of their composite history of active planning and research experience with scientific problems of the Bering Sea. Their cooperation is appreciated in lending an integrated perspective to consideration of research priorities within a broad balance of separate disciplines.

foreword

The genesis of the arctic program of the Office of Polar Programs, National Science Foundation, is described in the annual report of the President of the United States to the Congress on Marine Resources and Engineering Development, April 1970:

> Because of the arctic's overall significance and resource potential, arctic environmental research was one of the five initiatives selected by the President for immediate, priority attention. [The other four were coastal zone management, coastal zone research, lake restoration, and the International Decade of Ocean Exploration].
>
> 5. Arctic environmental research: Arctic research activities will be intensified, both to permit fuller utilization of this rapidly developing area and to insure that such activities do not degrade the arctic environment.

Since that time, the program has remained relatively small (receiving less than 10 percent of federal funds for arctic research) and has consisted of a few sharply focused interdisciplinary projects. The workshop reported herein is part of the continuing efforts toward program definition.

JOSEPH O. FLETCHER
Head, Office of Polar Programs
National Science Foundation

Washington, D.C.
20 March 1974

preface

This report takes its place among a succession of efforts on the part of U.S. scientists in recent years to reach a nationally integrated program for study of oceanography of the Bering Sea conducive to future cooperative study on an international basis.

The workshop held at Salishan Lodge, Oregon, in November 1973 brought together many U. S. participants of the First International Symposium for Bering Sea Study held in Hakodate, Japan, nearly two years ago. Proceedings of the international symposium have been published by the Institute of Marine Science, University of Alaska, as *Oceanography of the Bering Sea.* In the interim, several independent projects have been conducted by separate institutions and agencies in the U.S., paralleling national efforts likewise in Japan and the USSR. Joint international studies have been initiated through cooperative scientific activities between the U. S. and Japan and the U. S. and USSR.

It was the purpose of the workshop described herein to formulate a prospectus for a U. S. program in Bering Sea oceanography. The suggestions in this report are offered as a guideline in the preparation of specific research proposals for most effective response to scientific needs in this area of study.

D. W. Hood
Director, Institute of Marine Science
University of Alaska

Fairbanks, Alaska
15 March 1974

recommendations

THE BERING SEA WORKSHOP RECOMMENDS establishment of a PROBES program for long-range study of PROCESSES and RESOURCES of the BERING SEA SHELF

: : **Appraisal**

Continuing evaluation, recognition and synthesis of existing knowledge of the area of study and attendant impacts

: : **Research**

Multidisciplinary field and laboratory studies to comprehensively examine the physical environment, its living resources and the interacting processes by which its unique productivity is sustained and those threats by which it is endangered

: : **Logistics**

Provision for an iceworthy research vessel capable of working in high-latitude seas and development of shore-based laboratories in support of year-round polar studies

: : **Administration**

Program implementation through establishment of a U. S. national steering committee and international panel for coordination of priority logistic needs and standardization of data acquisition in accordance with PROBES objectives

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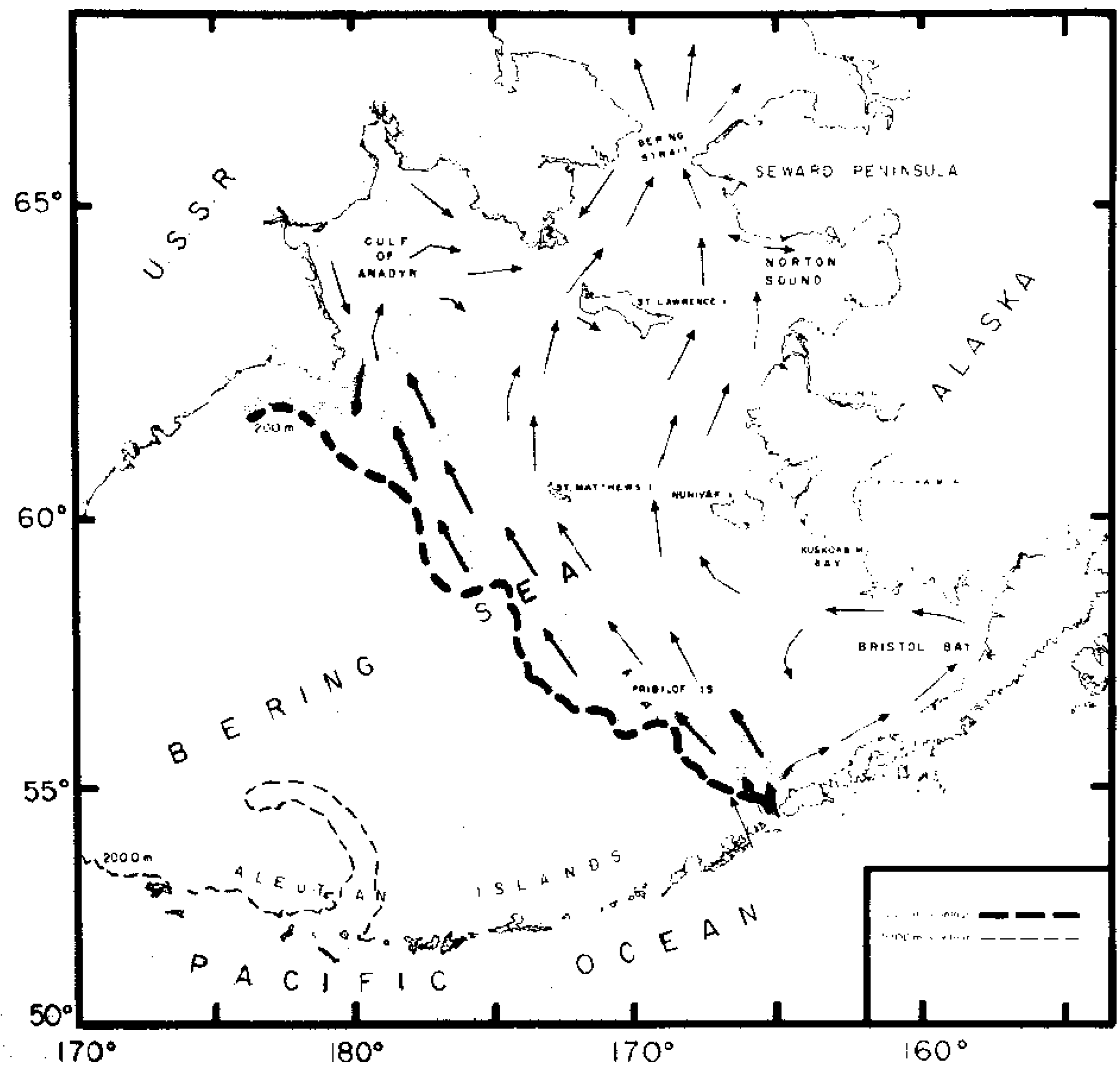
U.S.S.R
GULF OF ANADYR
BERING STRAIT
SEWARD PENINSULA
NORTON SOUND
ST. LAWRENCE I
ALASKA
ST. MATTHEWS I
NUNIVAK I
BRISTOL BAY
PRIBILOF IS
200 m
2000 m
BERING SEA
ALEUTIAN ISLANDS
PACIFIC OCEAN
65°
60°
55°
50°
170°
180°
170°
160°

Introduction

At Salishan Lodge we assembled from our various disciplines a hypothetical image of the dynamic and complex Bering Sea shelf system. The Bering Strait during the last 50 million years has been a migratory route between the Pacific and Atlantic oceans for marine organisms as varied as molluscs and mammals. At one time a land bridge spanning two continents, the Bering Strait provided the route for dispersion of Old World terrestrial plants and animals, including man, throughout the Americas. As recently as 20,000 years ago, the entire Bering shelf -- constituting 40 percent of the area of the Bering Sea -- was dry land and shelter for migrant species. The success of these migrations and the early subsistence cultures was largely attributable to the high productivity of the adjacent marine environment.

The contemporary Bering Sea, containing a volume of 3.7 million cubic kilometers of water, occupies an area about 2.3 million square kilometers between 51° and 66° N. The characteristic properties of its present waters are peculiarly modified by its exchange with the North Pacific Ocean through passes in the 1200 mile chain of Aleutian Islands. The narrow (85 km) and shallow (45 m) Bering Strait is the link with the Arctic Ocean and gateway to the northeast and northwest passages of historic prospect and commercial hopes through the centuries. The shallow feature of the Bering Sea (mean depth of 1636 meters) endows it with a sensitive heat budget that permits formation of a seasonal ice cover of remarkable consequences. During summer the waters are free of ice, but the temperature seldom exceeds 8 C.

Although warmer seas characteristically contain more diverse populations than colder waters, the high latitude seas support much larger numbers of individuals — due possibly to a greater effect of temperature on respiration rates than on photosynthetic rates. If relatively less photosynthetic energy is consumed in respiration, the energy thus reserved can support a larger biomass. A unique proportion of the Bering Sea is comprised of the most productive areas of the World Ocean — 53 percent is continental shelf and slope.

Ancient native cultures subsisted on a hunting and fishing economy for centuries in compatibility with an abundance of fish and animals in the Bering Sea area. Not until western man began exploiting the region to supply large populations of people with furs and fish was the natural living wealth of the area affected. As a result, the sea otter was exploited to the point of near extinction, flounder stocks were depleted, and the herring ecological niche appears to have been largely displaced by pollock. Still endangered, the world's largest salmon runs have been restored to a sustained harvest highly contingent upon rational fisheries management practice among all industrially participating nations. It has not been until the last decade that the wide diversity of the living resource potential of the Bering Sea has been fully appreciated and the threats to its perpetuation recognized. Large harvests of pollock, cod, ocean perch, black cod, halibut and rattails are now being taken by Japan, the USSR, and USA, and South Korea.

The shelf region of the Bering Sea features one of the largest marine mammal populations in the world, an abundant clam population, the largest bird populations per unit area in the world, the world's largest eelgrass *(Zostera)* beds; a high catch of pelagic fish per unit area; and some of the highest values of daily primary productivity ever measured.

Very promising oil and heavy-mineral provinces lie yet untapped on continental shelf portions of the Bering Sea. Extensive known mineral deposits exist on the land regions also, often accessible only by sea, and in submerged lands which will be developed through underwater placer mining techniques or by oil drilling. The extraction of these mineral resources is imminent and will impinge upon the habitats and ecosystems of the renewable resources. Only through an understanding of the total environment as an oceanic system will it be possible to resolve the conflicts that will inevitably arise from exploitation of both renewable and non-renewable resources from the Bering Sea.

Due to its high latitude location, the Bering Sea is characterized by very large annual variations in certain properties. Incident radiation varies annually from almost complete darkness to nearly total light; the extensive ice cover in winter poses further questions of how organisms maintain themselves during low-light periods and how the wind-driven ocean systems respond to changes in wind patterns.

Although productivity in polar seas with intermittent ice cover has been thought to be limited primarily by the high latitude seasonal deficiency of available light and lack of permanent thermocline formation, recent evidence (McRoy et al. 1974) indicates that the ice cover of the Bering Sea provides oceanographic conditions which in fact support high primary productivity on the undersurface of the ice during periods of the year when the water column itself is not productive. Moreover, the mass of tightly packed broken ice floes at times move southward, counter to the general northward direction of sea currents in the region. Sea ice transports sediments from the major freshwater systems of the Yukon and Kuskokwim rivers and may thus contribute to the presence of the unique proportion of primary productivity present at the shelf edge in support of one of the world's richest fisheries at that site. The seasonal ice cover of the Bering Sea is the hospitable habitat for abundant and diverse marine mammals and birds sustained by its associated productivity. It is possible that the seasonal ice pack may act as a giant pacemaker vital to regulation of the rich Bering Sea ecosystem.

The apparent high concentration of productivity at the shelf break invites detailed study to determine its cause. It may be related to local upwelling along the shelf break or in the Aleutian island passes; the high production associated with the ice edge during part of the year; or to a combination of these mechanisms and convective transports of organic matter in detrital form from other regions to be advantageously deposited along this feature of the sea.

Additionally, because the air masses above the Bering Sea sense the ice pack as an extension of the continent, the seasonal variability of sea ice may peculiarly modify the position and strength of the Aleutian Low storm system. In the world's atmospheric regime, the Bering Sea lies in one of the regions of maximum gradients and, hence, of maximum atmospheric vigor. The wind stress on the sea is an order of magnitude greater in winter than in summer. As a well-defined region, the Bering Sea is a tractable area for study of intense oceanic-atmospheric interaction.

The interrelationships of the Bering Sea shelf system and its processes are complex and their influences far-reaching. It is a system contributing to the food resources of many countries and probably to the weather of distant population centers. There is a great challenge to understand the Bering Sea — its biological processes, its dynamic physical regime, and its wealth of resources. It is to this we wish to direct our inquiring skills in the interest of science and rational resource development.

1
primary productivity and nutrient dynamics

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J. J. Goering
C. P. McRoy

Scope

Primary productivity

All primary production is controlled by the rate of supply of energy and by the rate of supply and redox state of nutrient elements. Productivity at all trophic levels is most readily assessed in terms of carbon, which occurs in only two principal redox states and is an important factor in community and system metabolism as well as air-sea interaction. The supply of nitrogen can limit production at all trophic levels, and the concentration of silicon can occasionally limit the abundance of diatoms — which are the principal photosynthetic organisms.

The annual cycle of organic matter production in the Bering Sea is unique as a consequence of the extensive shallow shelf of the sea, its relatively enclosed basin, and its seasonal cover of sea ice over the shelf. These features result in mechanisms that may individually operate in other ocean regions but function in combination only in the Bering Sea. This complex of mechanisms greatly enhances the total annual production beyond what would be expected for a sea situated on the edge of the Arctic.

Nutrient dynamics

The shallow shelf waters of the Bering Sea at times support an extensive growth of phytoplankton because light and abundant inorganic and organic nutrients are readily available. In shelf areas, nutrient supply is often attributed to proximity of freshwater runoff or to coastal upwelling. The importance of nutrient regeneration in bottom sediments, however, has not been investigated. It is contended that the sea bottom has been underestimated as a nutrient source and that it is a tightly coupled component of an interdependent shallow water ecosystem. Therefore, extensive studies of detrital organic matter decomposition in sediments as well as in the water column must be undertaken before the mechanisms and the importance of the in-place regeneration of nutrients in sustaining primary production in shelf water of the Bering Sea can be assessed.

Assessment

The production cycle begins in late winter with the development of a dense population of algae, mostly diatoms, on the subsurface of the sea ice. This bloom of ice algae appears to develop in the ice front zone and to move northward as spring advances.

The standing stock of the ice algae community contained within a few centimeters of ice is equivalent at peak stage to that of the entire 100-m water column in summer. The explanation for this remarkable phenomenon may come in part from the physical structure of sea ice, which consists of a series of passages and surfaces. A piece of ice 5 cm thick by 1 m^2 can have a surface area of 100 m^2.

In spring, the receding ice front creates a lens of low-salinity water. Initially, the seaward ice edge coincides roughly with the outer margin of the shelf. In this region, the initial spring increase of water-column phytoplankton begins in the wake of the melting ice. This bloom is presumably a result of the stability afforded by the lens of low salinity in combination with the seasonal increase in light. Also starting at the southern ice front, this bloom likewise moves north with the advancing season.

Yet another bloom of phytoplankton occurs in the open Bering Sea during formation of the seasonal thermocline. Equivalent to the classical spring bloom of temperate seas, the second bloom can begin as early as March near the Aleutian Islands and possibly not until late July in the Bering Strait.

The restricted connections between the Bering Sea and adjacent waters result in regions of active mixing, as evidenced by an area of upwelling just north of the Aleutian Islands and by high current velocities in the Bering Strait. In both cases, these physical processes sustain high summertime phytoplankton productivity.

The extensive shallow region and long coastline of the Bering Sea are a potential source of organic detritus. The Yukon and other rivers probably contribute significant amounts of particulate organic detritus to the Bering Sea. In addition, the extensive lagoon systems of the Bering Sea coast seasonally contribute much detritus in the form of seagrass *(Zostera)* leaves.

Discussion

The focus of these productivity mechanisms is the seaward edge of the Bering shelf, within the depth zone of 50 to 150 m. The patterns of the groundfish catch suggest a concentration of organic productivity at the edge of the shelf. The explanation for the concentration remains as the major objective for investigation.

In general, the cycling of the essential plant nutrients (nitrogen, phosphorus and silicon) in marine ecosystems is similar. We therefore propose that budget studies of only two of these elements be undertaken along with carbon in the shelf region of the Bering Sea. Since this sea is heavily harvested for organic matter (fish and mammal protein) by man, and nitrogen and silicon are often implicated as the nutrient species that limit plant growth in support of all marine productivity, we propose that an extensive study of nitrogen and silicon cycling be made. Such investigations should include studies of nitrogen and silicon consumption by primary producers; nitrogen and silicon regeneration through such processes as excretion and dissolution; *in situ* biochemical oxidation and nitrate reduction; convective and advective movement of nitrogen and silicon nutrients in shelf water and their movement through the sediments.

In order to define components of the marine nitrogen and silicon cycles, we have developed conceptual models depicting the various species and interrelationships of organic and inorganic nitrogen (Fig. 1) and silicon (Fig. 2) in the marine ecosystem.

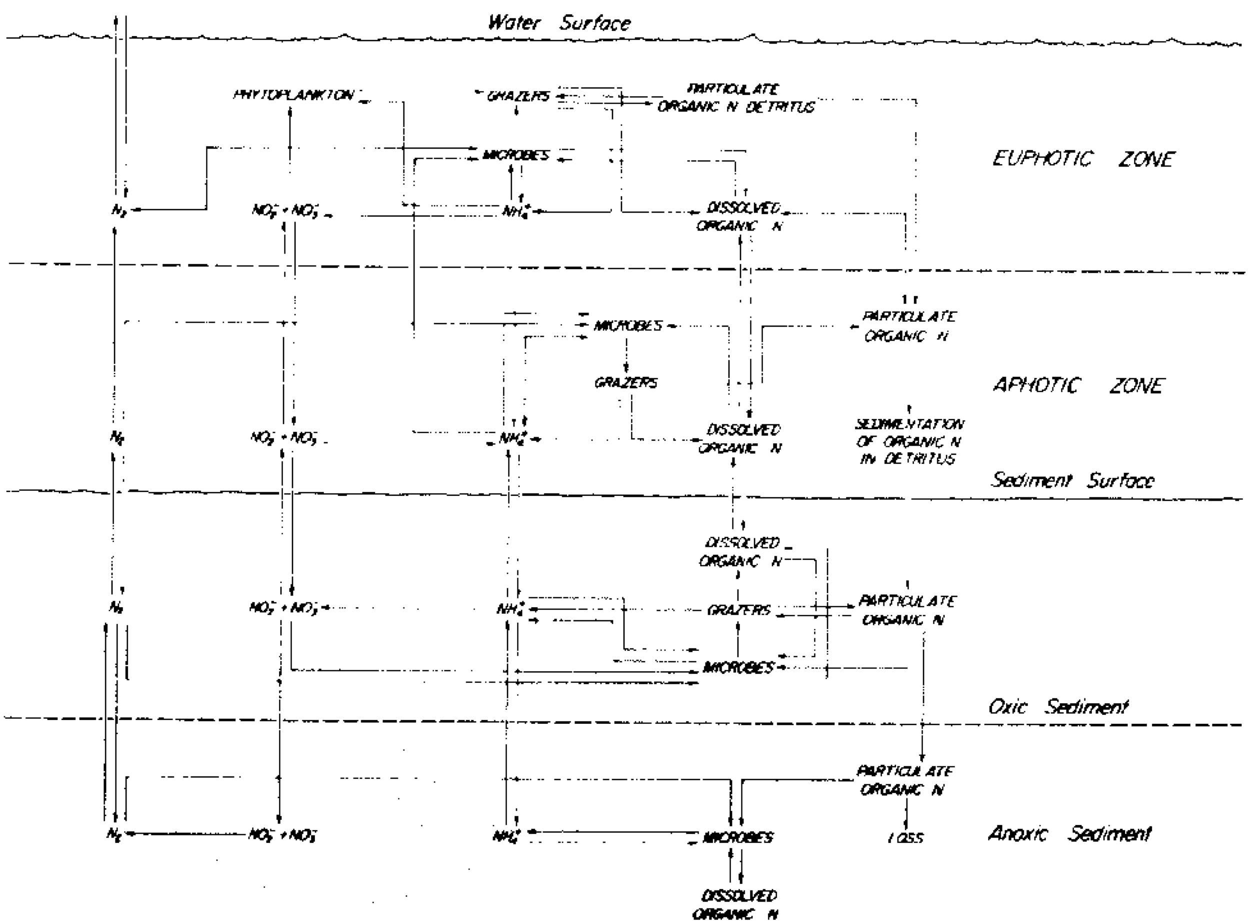

Fig. 1. **Biochemical cycle of nitrogen in the marine ecosystem.**

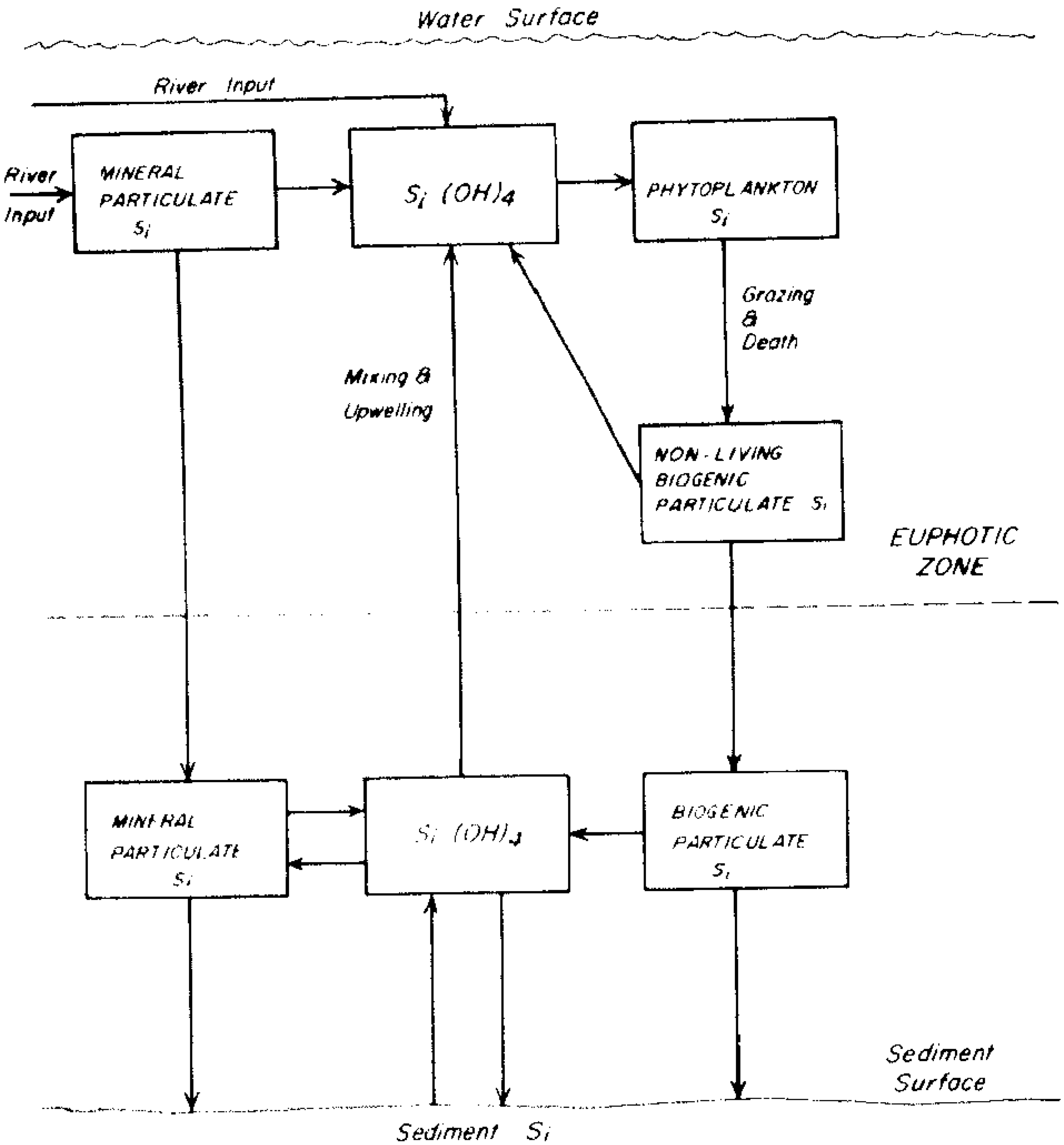

Fig. 2. Simple circulation of silicon in the sea.

The cycling of nitrogen and silicon in the water column is better understood than that occurring in the sediments. The nitrogen source of the bottom is sedimental organic matter, which is also the main medium for nitrogen loss from the water column. Organic matter is eventually buried in the sediments to become organic nitrogen in the anoxic layer. Nitrogen leaves the sediment biotic compartments as ammonia, both in oxic and anoxic layers. This species then either diffuses out into the water, is oxidized to nitrite or nitrate, or it is retained in the interstitial water by sorption onto sediment particles. The oxidized nitrate and nitrite species may be denitrified to N_2 and thence returned to ammonia by nitrogen fixation. Ammonia, nitrate, nitrite, and dissolved organic nitrogen can all be used for microbial growth.

RECOMMENDED RESEARCH GOALS:

1. *Choice of study area*

: : The shelf break area, within the block 54°-60°N and 165°-180°W should be given the highest priority, since this region includes the most productive fisheries for ground and demersal fish in the Bering Sea.

: : Second priority should be given to the seasonal ice sheet cover, particularly where it is contiguous with the shelf break, but also the edge of the sheet as it recedes in the spring.

2. *Hydrographic support adequate to assess nutrient budgets and cycles*

: : Nutrient budgets require hydrographic data on a mega-(10^{4}-10^{4} km/day) and meso-(1 to 100 km/min) scale. The first scale is required for system metabolism and air-sea research, and the latter is needed for sediment-water exchange and nutrient cycling research. We recommend that hydrographic support be adequate to compute mass balance and transport, upwelling rates, and vertical and horizontal eddy dispersion.

: : Independent estimates of carbon cycling are desired from geochemical mass balance observations, particularly as variations in annual heat content could profoundly affect the Bering Sea as a carbon source or sink.

: : Experimental observations should be designed to establish rates, routes and reservoir sizes for nutrient and silicate on the sea bottom interface, within the water column, at geographic boundaries, and at the pycnocline interface.

: : Particular attention should be given to rate limiting processes, including organic sedimentation, movement of nitrogen species and physical forms across the sediment-water interface, advective and convective supply of N species, nitrification and denitrification; soluble silica generation, uptake kinetics of N and silica by organisms, actual transport mechanism(s) involved in each process, and the specific role of zooplankton and *in situ* microbial regeneration.

: : Wherever possible, experiments should be performed *in situ* within a Lagrangian coordinate system.

3. *Primary production measurements*

: : Primary production in the Bering Sea should be estimated frequently enough (at least monthly) to establish the amount of carbon fixed each year. The absolute and relative contributions of various primary producer communities (seasonal ice cover, pelagic, and nearshore benthic associations — including macro-algae and seagrasses) should be obtained on a seasonal basis.

Observations should include species composition, species-specific photosynthesis, grazing and dispersion loss rates, metabolism rates of grazing organisms, loss rates to the benthos, grazing regeneration of nutrients, nutrient supply and regeneration as a function of meteorological and hydrographic processes.

Influences on primary productivity

: : Priority attention should be given to the possible role of the *seasonal ice cover* in providing nutrients, organic matter and substrate to browser and grazer organisms at the ice front; its role in providing organic matter to the water column and benthos, particularly during break-up and recession of the ice cover; and how it might control advective and convective redistribution of nutrient elements.

: : The nature of nutrient and light-limited production in a cold sea should be studied and the "true" rate of sustainable yield of food at high trophic levels determined, based on net primary production.

: : Determination of commercial impact on species composition of primary producers due to changes in abundance of top carnivores affected by commercial harvest; i.e., the effect of decreasing diversity at the top of the food web in systems of low initial diversities.

: : Effect of a low temperature sea surface on rates of community metabolism and responses to thermal variations.

2

secondary production: planktonic and benthic organisms

A. G. Carey, Jr.
H. M. Feder
C. Miller

Scope

Although the Bering Sea ecosystem might be expected to operate on the same broad scale as that found in marine systems elsewhere, the seasonal ice cover over much of the shelf suggests unique variations in energy flux and nutrient cycling. A description of the structural components of that ecosystem and estimates of the rates at which the underlying processes operate will lead not only to increased knowledge of such systems in general, but will also help to predictively define the differences attributable to the presence of a seasonal ice cover. An effective biological study of the Bering Sea will require a fresh look at the secondary production within the shelf ecosystem, utilizing the unique research opportunities provided by the special features of that system.

Assessment

Plankton

The plankton of the Aleutian Basin on the western side of the Bering Sea is well-known taxonomically and is similar to that of the western subarctic Pacific. One food web, utilizing small flagellates as the primary food source, is characterized by the small grazer copepod *Oithona similis*. The other chain, probably based on diatom production, is dominated by three species of large copepods: *Calanus plumchrus*, *C. cristatus*, and *Eucalanus bungii*.

Among a number of secondary food chains present in the Aleutian

Basin, euphausid herbivores seem to be less important here than in the subarctic Pacific region. Pteropods *Limacina helicina* are at times abundant or even dominant, but the conditions surrounding these blooms are not understood. As in the case of the subarctic Pacific, zooplankton of the Aleutian Basin is not common at the 100-200 m level. No species are known to concentrate in this specific depth zone, although seasonal migrants inhabit adjacent layers. An explanation for this widespread phenomenon remains a problem.

The zooplankton of the eastern Bering Sea is also described taxonomically, but the dynamics of its food webs are less clearly understood than they are in the Aleutian Basin. The dominant herbivores in the eastern region are thought to be *Acartia longiremis* and a species of *Pseudocalanus*, with two euphausids *(Thysanoessa raschii* and *Th. longipes)* also being important. The means by which these shelf species are able to overwinter under the ice in the Bering Sea is poorly understood.

Benthos

The macrofauna of the Bering Sea is well known taxonomically, and data on distribution, abundance, and feeding mechanisms are reported in the literature (Filatova and Barsanova 1964; Kuznetsov 1964; Neyman 1960; Stoker 1973). The relationship of specific infaunal feeding types to certain hydrographic and sediment conditions has been documented (Neyman 1960; Stoker 1973). However, the relationship of these feeding types to the overlying ice cover and its contained algal material is not known.

Mobile benthic species of king crab *(Paralithodes camtschatica)* and snow crab *(Chionocoetes bairdi* and *C. opilio)* occur on the southeastern Bering Sea shelf, where they are heavily exploited by commercial fishing fleets of several nations. Very little is known about the biology and distribution of most nektobenthic species such as mysid crustaceans. Extensive pandalid shrimp populations, consisting primarily of the northern pink shrimp *(Pandalus borealis)*, occur in great numbers of the southeastern Bering Sea shelf and along the nutrient-enriched continental slope; however, overfishing has drastically reduced the stock size of these crustaceans.

The biomass and productivity of microscopic sediment-dwelling bacteria, diatoms, microfauna and meiofauna have not been determined, and it is important that their roles be clarified. It is possible that these organisms are vital biological agents for recycling nutrients and energy from sediment to the overlying water mass (see Fenchel 1969 for review). Of unique interest is the potential relationship of the ice edge and underice primary productivity blooms to the underlying benthic-biotic-chemical system.

Crabs and bottom-feeding fishes of the Bering Sea exploit a variety of food types, benthic invertebrate species being most important. Most of these predators feed on the nutrient-enriched upper slope during the winter, but they move into the shallower and warmer waters of the shelf of the southeastern Bering Sea for intensive feeding and spawning during the summer. Occasionally they exploit the colder northern portions of the shelf. This differential distribution is reflected by catch statistics which demonstrate that the southeastern shelf area is a major fishing area for crabs and bottom fishes. The effect of intensive predatory activity in the southern versus the northern part of the shelf appears to be partially responsible for a difference in standing stock of the food benthos in both regions (Neyman 1960, 1963). It is apparent that bottom-feeding species of fisheries importance are significantly exploiting a restricted portion of the Bering Sea shelf and are cropping generally slow-growing species such as polychaetous annelids, snails, and clams. Thus, the carrying capacity of the shelf for benthic fisheries organisms appears to be related to the level of the standing crop of important slow-growing species in the Bering Sea; however, nektobenthic and pelagic Crustacea such as amphipods and euphausids may grow more rapidly in the nutrient-rich water at the shelf edge and may provide important food resources. An intensive examination and comparison of predatory activity and its impact on the benthos should be undertaken in southern and northern shelf regions.

Some marine mammals of the Bering Sea feed on benthic species. Walrus feed predominantly on slow-growing species of mollusks, but seals prefer the more rapidly growing crustaceans and fishes in their diets. Although showing food preferences, marine mammals are opportunistic feeders. As a consequence of their broad food spectrum and their exploitation of secondary and tertiary consumers, marine mammals are difficult to place in a food web and to assess in terms of energy cycling. Intensive trawling activities on the Bering Sea shelf will ultimately have important ecological effects on benthic organisms used as food by marine mammals. If benthic trophic relationships are altered by this intensive fishing activity, marine mammals may have their food regimes altered. Adaptable species will survive, although perhaps initially in reduced numbers.

Discussion

Plankton

The Bering Sea has three distinctive features important in evaluation of zooplankton dynamics: (1) The number of species present is low and well-known taxonomically. In addition, very few of these achieve importance in terms of either individual numbers or biomass; probably not more than 25 species adequately represent the quantitatively important species. (2) The continental shelf of the Bering Sea is very wide in contrast to the corresponding subarctic Pacific region. This large expanse of shelf will aid in explaining the important differences in faunal composition observed between the neritic and oceanic regions. (3) The seasonal ice cover over a large part of the continental shelf permits study of overwintering mechanisms under conditions very different from those in the more southerly parts of the range of shelf-inhabiting species.

The broad, productive shelf of the Bering Sea undergoes rapid transition to a deep basin environment. It has been shown that the composition of benthic fauna changes dramatically with depth down a steep continental slope in response to marked modification of the physical environment (Rowe and Menzies 1969; Sanders and Hessler 1969). An examination of the effect and controlling features of a steep depth gradient into the cold, high-latitude Bering Sea on the distribution and abundance of benthic fauna will provide valuable insights. The reduced temperature gradient and the marked seasonality of primary production in the Bering Sea are of particular interest.

Most of the carbon produced in a marine ecosystem is channeled through invertebrate species, many of which interact in food webs that terminate in commercially essential food species. The harvesting of great numbers of certain commercially valuable species such as shrimps, crabs and demersal fishes in the Bering Sea could eventually result in their replacement by and subsequent drastic increase in the standing stock of commercially less desirable forms such as sea stars. Heavily exploited areas should be studied to provide insight into possible significant perturbations of the natural food web. The documentation of recent exploitation of Bering Sea fishery resources makes this area well-suited for such research.

The basis of secondary production must be understood before the significance of high standing stocks and high yields of commercially important species can be understood. Knowledge of rates of growth, mortality, recruitment, and metabolism is scanty. The few data available indicate that growth rates of organisms such as pelecypods are low, although the biomass of commercial species removed each year suggests a large benthic food source. Thus, certain benthic species with high growth and reproductive rates should be identified and examined. Basic population dynamics studies of important prey species are necessary to understand the rates of energy transfer across trophic levels to commercially important species.

There is a lack of basic information in marine ecosystems on the degree of interaction between organic matter in the surface waters and that on the sea floor. We also must define and measure the sources and input rates of detritus in the Bering Sea. These are data fundamental to the understanding of any marine ecosystem function, since much of the benthos derives its food from detrital materials. Such information is thus essential also to a meaningful understanding of the Bering Sea itself.

RECOMMENDED RESEARCH GOALS:

Planktonic production

1. *Determination of the distribution and abundance of the Bering shelf zooplankton species in relation to environmental*

gradients and to seasonal changes

: : Characterization of the neritic-oceanic zooplankton boundary across the broad continental shelf to determine the causes for the transition zone

: : Studies of of the vertical distribution of the zooplankton in relation to water characteristics to explain the exclusion of much of the fauna from the 100-200 m depth zone

2. *Determination of the dynamics of the Bering Sea pelagic food webs*

   : : More complete information on trophic interactions and rates of energy flux

3. *Determination of zooplankton life cycles in subarctic seas, particularly overwintering forms beneath the ice.*

Benthic production

1. *Determination of the distribution and abundance of benthic fauna and of the structure of benthic communities in relation to the environmental gradients*

   : : Sampling across the uniquely broad southeastern continental shelf and down the continental slope, with particular reference to the seasonal ice cover and shelfbreak

   : : Comparison of the northern and southeastern continental shelf regions with particular reference to seasonal ice cover and benthic predators

2. *Determination of the structure of the benthic food web with particular reference to the diet of predaceous commercial species*

   : : Comparison of the food web in the northern and southeastern continental shelf areas and along the continental shelf break and upper slope

   : : Characterization of the marine mammal-benthic fauna food web

   : : Determination of the quality and quantity of particulate organic carbon input to the sea floor with particular reference to the under-ice primary production

3. Biological description of dominant species of the benthic communities and important food sources to commercial species

   : : Population dynamics, including species population growth, recruitment, and mortality estimates

   : : Feeding rates with particular reference to seasonality

   : : Metabolic rates of dominant macrofauna

4. *Determination of benthic community energy use, including community metabolism, to define the partitioning and use of energy in the detrital food web on the sea floor.*

3
fisheries

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H. Kasahara
L. L. Low

Scope

Food web studies

A better understanding of food webs is essential to production studies of higher trophic levels in the ecosystem of the Bering Sea. In approaching this problem through a better description of the feeding characteristics of harvestable fish species, some of the major pathways for energy transfer could be traced from harvestable stages back to lower trophic levels. Although limited information is available, a systematic program of stomach content analysis is needed.

Evaluation of existing harvestable resources

Assessment of abundance and yields of harvestable species is an important subject not only from the viewpoint of fishery management, but also as related to man-made changes in the abundance and composition of organisms at higher trophic levels.

Prediction of recruitment

Appraisal of potential fishery resources has been made to some extent, but further studies on quantitative aspects (abundance and potential production) are desirable. As fishing is intensified, the number of age-groups in the stock usually decreases with time. In temperate and tropical waters, it is not infrequent that a fishery is supported by only one age group. Even in subarctic waters, some fisheries, including now the Bering Sea pollock fishery, take the bulk of their catches from only two or three age-groups.

The problem of predicting recruitment in advance of the fishery is not only critical for the maintenance of the fishery but also represents one of the most challenging research topics facing fishery scientists today.

Assessment

The current annual catch from the Bering Sea is 2.5 million tons, which is about 4 percent of the total world marine catch. The history of intensive fishery efforts in this region is relatively short (15 years, see Fig. 3), and a large volume of data is available both from commercial fishing and exploratory surveys. A substantial amount of work has already been done, but much remains to be accomplished, particularly in terms of analysis and interpretation.

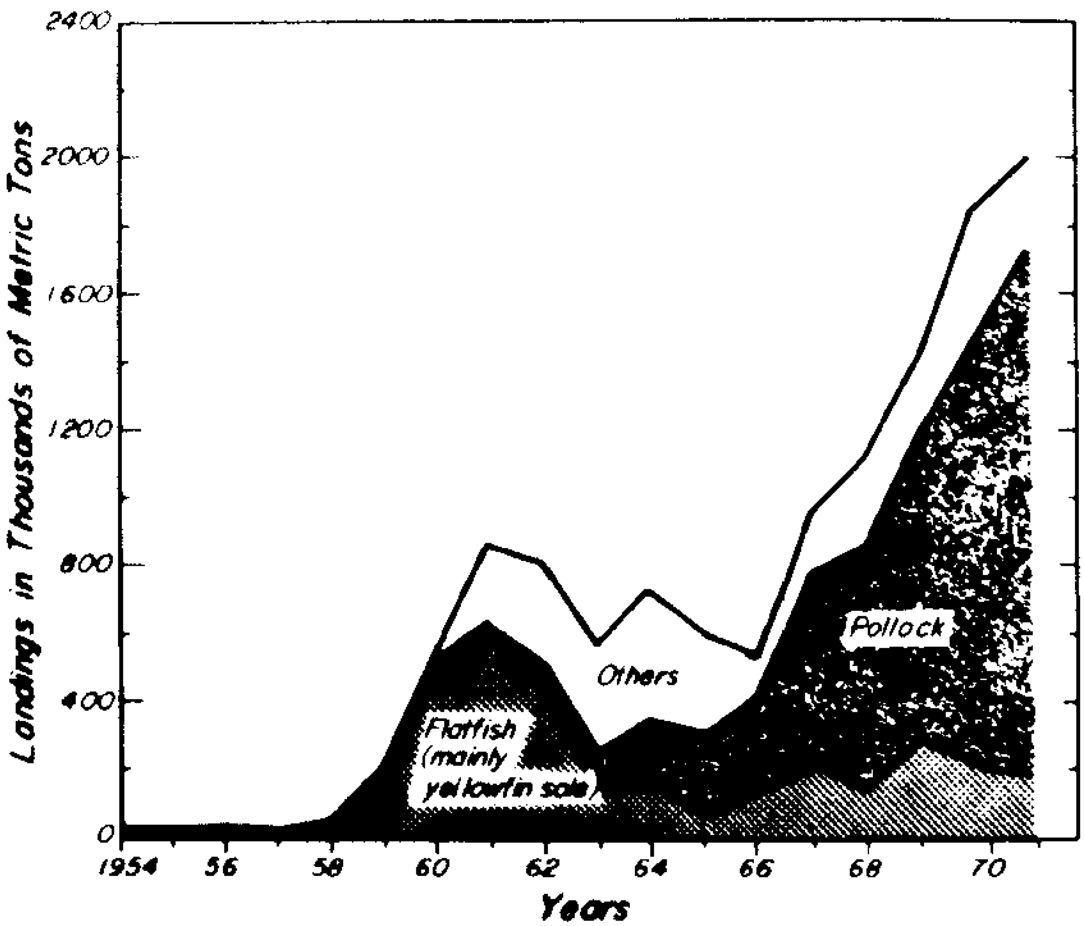

Fig. 3. Estimated landings of flatfish, pollock, and other species of bottomfish by all nations from the Bering Sea during 1954-71 (Pruter 1973).

Most demersal species are already fished intensively, but observations of stomach contents suggest that such forms as capelin and sandlance exist in relatively large numbers. Squids, bathypelagic fishes, and some of the larger zooplankton may also be considered resources for future exploitation.

Although some food web information is available, a systematic program of stomach content analysis appears in order. This investigation might be implemented by placing observers on large commercial vessels operating seasonally in the area. More difficult is the determination of

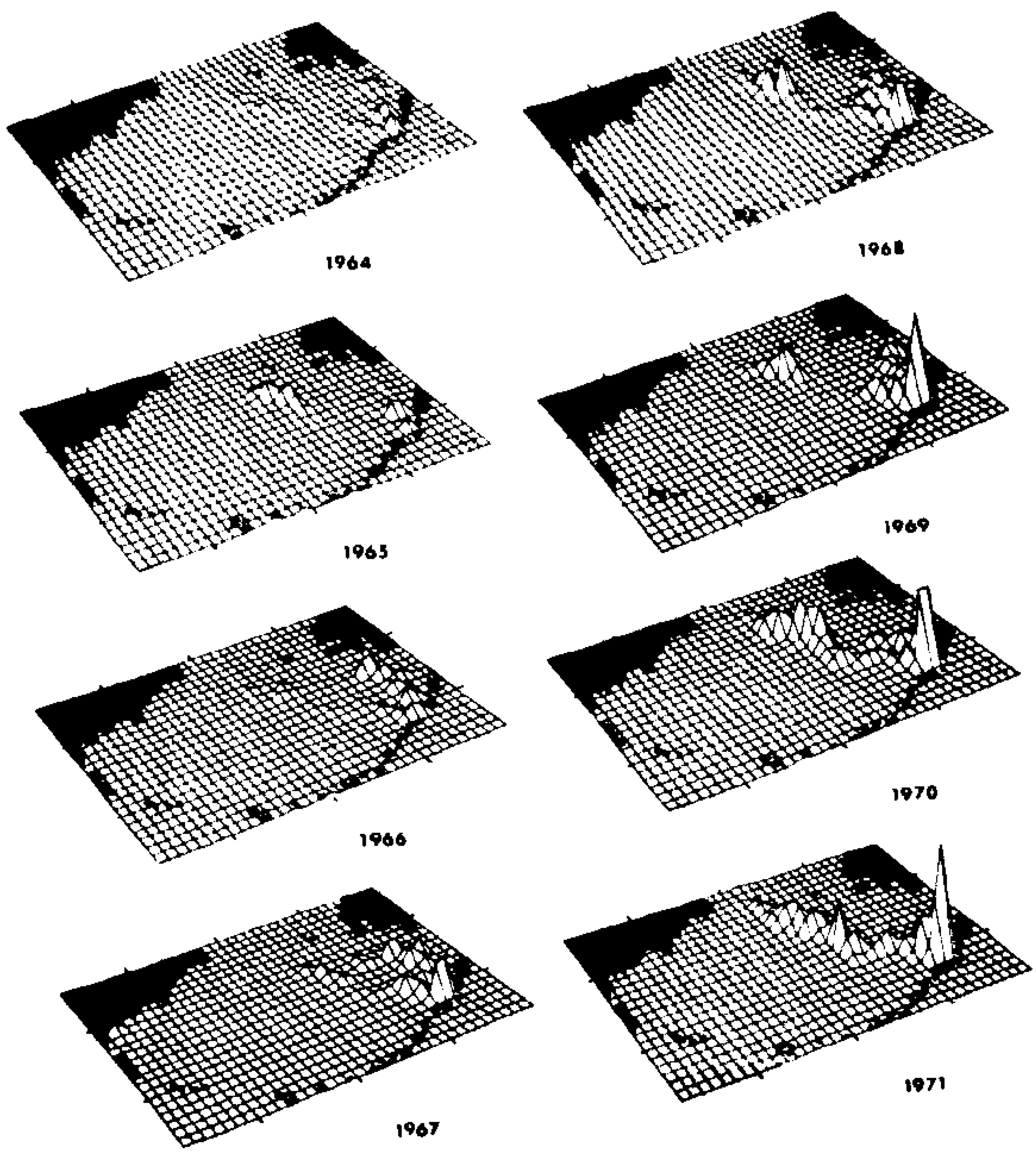

Fig. 4. Time-series graphs showing relative annual groundfish catch by Japanese mothership, longline-gill net and independent trawl fisheries in the Bering Sea, 1964 – 1971 (Brown and Low 1973).

rates of consumption of prey organisms. This would be done, to the extent practical, within limits of existing methodology. A clear understanding of food web relationships between stocks of interest must involve interactions with plankton, mammal, and seabird scientists working in the same program. Also, since large populations of marine mammals and sea birds compete with man for some of the same resources, changes in these populations may be expected as stocks are significantly reduced. The extent of physical effects of fishing operations, especially the disturbance of bottom sediments might also be considerable; particularly in the southeast corner of the Bering Sea where trawling is intensive (Fig. 4, previous page).

The removal of large quantities of fish and invertebrates from a relatively limited area (e.g., see Fig. 4 for Bering Sea demersal stocks) must have substantial *effects on the ecosystem of the area.* Although means available to study this subject are rather limited, analysis of existing data over the entire period of intensive exploitation might give some clues, for example, in terms of changes in the relative abundance of prey, predator and competitor species.

One problem in evaluating commercial catch information is access to existing information. Much of the excellent data collected from foreign commercial fisheries has been made available only to limited groups of scientists under international arrangements. Moreover, there have been constraints on the publication of the results of research based on such data. These restrictions make it difficult for competent scientists in the academic community to effectively participate in planning and conducting meaningful research.

RECOMMENDED RESEARCH GOALS:

1. *Food-web studies to determine the characteristics of harvestable species in different stages of their life histories*
   : : Studies should focus on major species of goundfish (e.g., yellowfin sole, turbot, rock sole, flathead sole, Alaska plaice, Pacific halibut, black cod, Pacific cod, Pacific Ocean perch, Pacific pollock, and sandlance); pelagic fishes (e.g., herring, salmon, and capelin); and invertebrates (e.g., crabs and shrimps)
   : : Whenever possible, rates of consumption of prey organisms should be estimated.

2. *Assessment of abundance and yield of harvestable species*
   : : Analysis of fisheries data from commercial fisheries and from exploratory and survey cruises
   : : Analysis by species, time and location of historic changes and present status

3. *Prediction of recruitment*
   : : Early detection of year-class fluctuations
   : : Stock-recruitment relationships

4. *Effects of harvesting on the ecosystem*
   : : Trophic effects on prey, predator, and competitor species
   : : Physical effects of fishing operations

5. *Appraisal of unexploited potential species*
   : : Abundance, potential yield and harvesting methodology of lesser known species (e.g., capelin, sandlance, squid and large zooplankton).

4
mammals and birds

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Scope

The Bering Sea possesses a unique diversity and abundance of marine mammals, far exceeding those along other American shores, and boasts the greatest variety anywhere in the world of marine mammals associated with pack ice. The Bering Sea is one of the most productive areas for seabirds in the western hemisphere, probably equal to or surpassing in productivity the renowned waters off the Peruvian coast.

By far the major activity of Bering Sea mammal and bird populations is concentrated over the continental shelf, the same region which delineates the maximum extent of seasonal ice. The concentrations of these populations and the behavioral, physiological and biochemical aspects of their special environmental adaptations have particular significance for scientists interested in the biology of the marine environment. Comprising the top trophic level of what is clearly one of the most productive bodies of water in the world, these species offer an abundance of challenging research opportunities. The processes of productivity which support their existence, as well as the interrelationships among members of the system, are open to exploration.

The sea ice provides an ever-replenishing matrix for primary productivity, functioning at the same time as a living platform, breeding ground, climatic barrier and migratory route for the Bering Sea mammals and birds. Many questions exist with respect to the relationships between these animals and their peculiar habitat. The role of the mammals and birds as re-distributors of nutrients in and over the surface of the sea is not clear, but the estimated quantity of their excretory products suggests that it might be an important contribution. Many possibilities exist for research related directly to the ecology of the Bering Sea region as well as to the adaptations of the fauna of that region. The potential exists for biological generalizations with implications for our understanding of life processes and for conservation and utilization of these resources

Productivity

Most of the 25 species of Bering Sea marine mammals are part-time residents (Fay 1974). Walrus and several kinds of seals and whales move down into the region in winter with the advancing sea ice from the north, whereas others move into the region from the south in the ice-free summer. Prorating their occurrence in terms of full-time residence in the Bering Sea, the marine mammalian fauna is equivalent to 1.5 million full-time residents having a biomass (standing crop) of about 450,000 metric tons. They consume some 9 to 10 million tons of nekton and benthos annually (4 times the commercial fisheries catch), converting at least 10 percent of that into new flesh and redistributing as feces more than 1 million tons of nutrients. These estimates are rough but conservative, and better data are needed for more realistic assessments.

The ribbon seal and the largha harbor seal occur only in the Bering and Okhotsk seas; the Pacific walrus is found only in the Bering and Chukchi seas (Scheffer 1958). The bird life is similarly concentrated in the moving seasonal ice and must be sustained by the high productivity found there. Several avian species, notably those of the auklets, are found only in the Bering Sea (Fay and Cade 1959). The density of bird life in the eastern Bering Sea probably exceeds that of any other location in the Western Hemisphere, with the possible exception of the Humboldt Current regions off Peru.

Birds also are a significant but poorly understood component of the Bering Sea ecosystem. There are about 40 species of birds that frequent the Bering Sea (Gabrielson and Lincoln 1959) and are classified as "seabirds," including 14 of the 23 known species of Alcidae in the world. They spend most of their lives at sea, usually coming ashore only to breed. More than 50 species of other birds, not generally regarded as "seabirds," frequent the coastal waters and littoral zone, where they utilize marine resources on a seasonal basis.

Comparative data on wintering seabirds (Shuntov 1966) indicate that bird densities of from 27 to 45 birds per km^2 in the southern portion of the Bering Sea are 2 times greater than those densities encountered in the Pacific Ocean near Japan, 3 times greater than in the Sea of Japan, and from 10 to 20 times greater than those found in both the South China Sea and the Indian Ocean. Summer densities, if comparative information were available, would likely increase the differences.

Imprecise information on populations and population turnover because of migration, mortality and natality permit only crude estimates of production variables. The standing stock of seabirds is estimated at 27 million birds weighing 14,500 metric tons. Of this biomass, there are 135,000 birds weighing 135 metric tons; these are primary consumers that feed on 34,700 metric tons (wet weight) of plant material, largely eelgrass, in a year. Another 26.5 million birds weighing 14,315 metric tons are secondary consumers that eat 1.0 million metric tons (wet weight) per year.

The migratory birds that reside in the Bering Sea during much of their lives and those that rest and feed there during biannual migrations are part of an international resource that is seasonally shared by many people of several nations. Birds using the Bering Sea migrate southward along both sides of the Pacific Ocean; some, such as the arctic tern, even reach Antarctic waters.

The shearwaters that summer in the Bering Sea are commercially harvested in their breeding grounds in Tasmania and south Australia. The unfledged young (or, "mutton") birds are killed for meat and oil under government regulations and quota limitations. Seabirds and their eggs are also harvested for subsistence by coastal native peoples.

Treaties between the United States and Canada (1916), Mexico (1936), and Japan (1972) provide a measure of protection for most migratory birds found within the Bering Sea and prescribe species, methods and manners for harvest. A similar treaty is being negotiated between the United States and the USSR.

Discussion

National importance

The American people have indicated through the Marine Mammal Act of 1972 their intense concern that marine mammals and their environment be carefully conserved in a healthy state. Much of the knowledge required to do that is not yet available and must be obtained if the Marine Mammal Protection Act is to be effectively implemented.

The diversity and abundance of marine mammal and bird species in Alaska, compared to the situation along the shores of the other states, suggest that American scientists interested in marine mammal biology will find the last frontier for many of their studies in the Bering Sea region.

Birds and mammals are an important system for transporting, both vertically and horizontally, energy and nutrients within the Bering Sea. For example, the tiny crested auklet (230 g) has been reported to dive to 120 meters to catch prey, and murres take their catch to young that are more than 40 miles away at the nesting colony. Birds defecate in the water during feeding and also on the nesting cliffs. Guano defecated by these birds may exceed 100,000 metric tons per year; however, guano accumulation in colonies is negligible because precipitation leaches deposits — thereby carrying most nutrients back into the sea.

International implications

The marine mammals of the Bering Sea constitute a renewable resource whose harvest is shared by the United States, the Soviet Union, Japan and Canada. Those four nations are bound by the conditions of the International Fur Seal Treaty by which the sustained annual yield of approximately 50,000 individuals of that species at the Pribilof Islands is determined. The products, fur and animal food, are divided among the signatory nations. The commercial harvest of other seals and of whales in the Bering Sea by the Soviet Union amounts to about 20,000 animals each year; there is no commercial harvest at present by the United States, since passage of the Marine Mammal Protection Act of 1972 prohibits it. Subsistence hunting by peoples on each side of the Bering Sea accounts for an additional 6000 animals annually. Altogether, about 76,000 individual marine mammals are harvested, representing a biomass of 15,000 metric tons and a monetary value of about 9.5 million dollars per year. Efforts are required to develop effective conservation and management of these resources through cooperative programs. A step in that direction was taken in 1972 by initiation of the U. S./USSR Environmental Program Agreement, which included provisions for joint efforts to conserve wildlife. The first implementation of the program took place in 1973 by the participation of two Soviet marine mammal biologists in the research cruise of the *Alpha Helix* in the Bering Sea.

Aside from the poorly known role of birds in the functioning of the Bering Sea ecosystem, the avain resource is of other values to man. Marine birds have long been a part of the Alaskan natives' culture and, to a lesser degree today, an important source of food and clothing for Eskimos and Aleuts of the Bering Sea. Bird carcasses and eggs add variety and nutrition to the diet. Bird skins were formerly used for clothing, and feathers are still used for ornamentation. Harvests of seabirds and birds of the estuarine habitat and their eggs by Alaskan natives probably exceeds 10 metric tons per year, valued at $25,000 – $35,000.

Marine birds have intrinsic and esthetic values which are difficult to assess. National interest in seabirds and other migratory birds in the Bering Sea is evidenced by the presence of eight national wildlife refuges in the area, including those of the Yukon Delta, St. Matthew Island, Cape Newenham, Izembek Lagoon, and most of the Aleutian Islands. Additional refuges are being proposed under provisions of the Alaska Native Claims Settlement Act to protect seabird nesting colonies and to provide areas where seabirds can be observed in undisturbed habitats.

Potential conflicts of interest

Impending developments of mineral and petroleum exploitation and further expansions of fisheries in the Bering Sea will have some predictable effects on the marine mammal and bird populations, as well as on other levels of the ecosystem, through perturbations of habitat and competition for food supplies. Much more information is needed to evaluate this potential. Conceivably, the impact of these exploitative industries, mainly on the benthic and demersal fauna of the shelf, could greatly lower the carrying capacity of this habitat for marine mammals and birds.

The feeding niches of most species of seabirds are poorly known, especially on a year-round basis. Population data on birds of coastal Alaska are lacking and not of sufficient precision to detect possible declines in bird numbers for whatever cause. Commercial fisheries are causing directly mortality to birds which become entangled in gear during feeding and drown. Crude estimates suggest that Japanese salmon fisheries are taking 225,000 to 750,000 birds annually in gill nets off the Aleutians Islands. The impact of this mortality upon the viability of local bird populations is not known. Exploitation of offshore petroleum deposits and marine transportation of oil through the Bering Sea are potential future causes for attrition of seabird populations in these waters.

Unique research opportunities

We need to know much more about the physical aspects of the pack ice itself, especially its gross morphology — the size of floes, their thickness and surface texture, and the amount of open water between them — and the kinetics, direction and rate of ice movement. It is already apparent that these conditions can exert important influences on the distribution and welfare (therefore, the productivity) of the marine birds and mammals that normally reside within the boundaries of the pack or are excluded from that area when ice is present (Burns 1970; Fay 1974). Specifically, for example, we need to know: (1) How the distribution of open water and types of ice are related to the distribution of each species; is this a biologic preference of the species for certain ice conditions, or more a function of other factors such as climate and availability of food? (2) How the movements of the pack ice affect the distribution and energy expenditure of each species; that is, do the animals drift with the pack and therefore distribute their impact on the food supply over a very wide area, or do they actively maintain their position and thereby utilize more energy and concentrate their effects in a smaller, more restricted area?

It is particularly important that the significance of experimental biology and potential biological generalizations not be overlooked in the thrust toward exploratory and descriptive ecosystem studies. The special features of environmental adaptation associated with a cold marine milieu are worthy of our best research efforts. Natural adaptations of maintenance of homeothermy are an example, and a diverse and abundant selection of species such as is represented in Bering Sea populations is essential for successful implementation of these studies. Many of the adaptations best observed in natural populations are of importance for what their study can contribute toward our understanding of topics important to the health sciences. The importance of studies of diving physiology in seals, for example, has led directly to comparative studies contributing much to our understanding of the physiology and pathology of asphyzia, its consequences and natural defenses (Elsner 1969).

RECOMMENDED RESEARCH GOALS:

1. *Population studies of marine mammals and birds*
   : : Development of survey methods for improved assessments of numbers, population composition, migratory patterns, distribution and relations of each major species to structure and movements of ice; natural history factors of mortality, pathology and parasitology
   : : Modeling of populations to predict consequences of increases or decreases of populations upon various components on the Bering Sea and, conversely, to determine factors of the Bering Sea that affect seabird and mammal populations

2. *Trophic relations of key species*
   : : More complete information on trophic interactions, nutrition and energetics, dependencies and impacts on other biotic parts of the system

3. *Adaptation processes*
   : : Functional anatomy and physiological ecology; comparative ethology, biochemistry and physiology of adaptations of marine birds and mammals to arctic and ice-covered seas.

5

chemical oceanography

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Scope

The Bering Sea lends itself exceptionally well to investigations of physical, chemical and biological budget studies because of its relatively restricted proximity to the adjacent Arctic and Pacific ocean waters and present lack of reliable year-round oceanographic data. A dominating physical feature of the Bering Sea is its winter ice-cover over most of the shelf region. Many of the chemical source materials to this region are identified; the importance, however, of each substance on an annual basis is poorly understood. It should be possible to define these chemical sources and processes vital to high productivity in the deepwater, shelf and slope regions, once a better understanding is reached of the heat and salt budgets and the amounts and forms of carbon, nutrients and trace elements. Such information would allow the assignment of transfer functions between chemical reservoirs to enable the construction of a meaningful material balance model of the Bering Sea.

Assessment

Rivers and lagoons

The Bering Sea receives runoff from four major rivers: the Yukon and Kuskokwim entering from Alaska, and the Anadyr and Kamchatka originating in Siberia. Data on amounts and seasonal distribution of freshwater added by these rivers have been assembled and reviewed by Roden (1967). Average annual river discharge (m^3/sec) to the Bering Sea has been reported as 6224 from the Yukon, 1270 from the Kuskokwim and 473 from the Kamchatka. Due to their high-latitude drainage basins, these rivers are fed largely by snow and ice melt, and their flow arrives essentially in one volume during the summer. The mean annual discharge of the Yukon River, the largest river flowing into the Bering Sea, is about the same as that of the Columbia River (6037 m^3/sec) into the Pacific Ocean. During peak discharge in June and July, the Yukon River discharge approaches that of the Mississippi River. Flow volume from the Yukon River during June, July, and August accounts for 60 percent of its mean annual contribution to the Bering Sea with 90 percent of the total input occurring between May and October.

The coastal lagoons surrounding the eastern Bering Sea contain dense stocks of eelgrass. Tidal action exchanges a large proportion of the lagoon volumes daily and supplies the Bering Sea with as many important geochemical species as are found in seawater. Each of these lagoons contributes on an annual basis a volume of water equivalent to the input of a large river. In contrast to river contributions, however, the lagoon input is not subject to 20-fold seasonal variations in volume each year.

Sediment and in-situ processes

Input to the Bering Sea is generally considered to be an *in situ* regeneration process. Water-sediment reactions usually involve the release of silica, and the regeneration processes are usually biologically mediated — often occurring on detrital material which is transported to the sediments. Chemical species produced by regeneration or decomposition reactions often accumulate to high concentrations in interstitial environments due to restricted circulation. The supply of the regenerated nutrient species is governed by molecular diffusion (typically 10^2 to 10^3 times slower than eddy diffusion) and other mixing processes. Concentration differences between interstitial layers and overlying waters can differ by an order of magnitude, and freshwater inputs can therefore significantly affect the chemistry of the receiving waters.

Air-sea interaction

The questions of mass exchange across the sea surface usually fall within the scope of chemical oceanography and material balance studies. A notable parameter in such investigations is carbon dioxide concentration, which is a fundamental factor in primary production. Past measurements of the partial pressure of CO_2 in surface seawater of the Bering Sea have shown that the gas is an excellent tracer for both physical and biological processes occurring there (Kelley and Hood 1971; Park 1967). Principal features of PCO_2 distribution in the Bering Sea are intense undersaturation of -100 ppm in the northcentral part, general undersaturation of about -60 ppm in the western part, and supersaturation conditions in the eastern part (Gordon et al. 1973).

Aleutian island passes: upwelling

Vertical transport of deep water is known to occur in the vicinity of the Aleutian island passes, with characteristic high nutrient and CO_2 concentrations present in the near-surface waters. This phenomenon has been investigated in Samalga Pass (Kelley and Hood 1971) within a region of intense vertical mixing, during which studies carbon dioxide partial pressures exceeded 500 ppm, with NO_3^--N levels in excess of 30 µg-atoms/liter. Previous evidence of upwelling near the margin of the continental shelf, which extends along the 400-m contour line from Unalaska Island to the Pribilof Islands, is suggested by sharp gradients in surface NO_3^--N concentrations, (Dugdale and Goering 1966) varying from 15 µg-atoms/liter to undetectable levels between stations separated by less than 30 n. miles.

Sea-ice chemistry

The chemical composition of sea-ice and its importance as a nutrient source has been implied by McRoy and Goering (1974). It is not clear what effect the freezing process has on seawater composition (Nelson and Thompson 1954), although there is indication that major constituents such as sulfate and alkalinity may be modified by sea-ice formation (Hood and Reeburgh 1974). The growth of ice algae during spring suggests that organic compounds may be concentrated on ice platelets and transported with the ice to the zone in which the spring melt occurs. The effect of ice formation in shallow water as a water column homogenizing process may also be important.

Bering Sea fertility and chemistry

Recent statistics show that the annual Bering Sea commercial fish harvest is approximately 2.5 million metric tons. If the catch is 10 percent carbon, this harvest represents an annual removal of 2.5×10^5 metric tons of carbon (2.5×10^{11} g carbon, 2×10^{10} moles carbon). Assuming a C:N ratio of 7:1, 2.8×10^9 moles of nitrogen are removed and transported to the dinner tables of other countries.

When we further assume that the fishery ground comprises about 10 percent of the total area of the Bering Sea (2.3×10^6 km^2), assume also that the winter vertical mixing does not extend below 150 m, and if we consider that 100 m is the effective depth of nitrogen nutrients that are usable by the food web, the volume of the Bering Sea water exposed to fishery production is approximately 2.3×10^{16} liters, according to the following computation: (2.3×10^7 km^2) x 100 m = 2.3×10^{13} m^3 (or 2.3×10^{16} liters). The available proteinaceous nitrogen, assuming 20 µM NO_3^- /liter, is (2×10^{-5}) (2.3×10^{16}), or 4.6×10^{11} moles nitrogen. The annual percentage removal of nitrogen is 2.6 $\times 10^9 / 4.6 \times 10^{11}$, or about 0.6 percent of the available nitrogen in the sea. Although this calculation assumes a steady-state condition for the Bering Sea and does not consider a nitrogen reservoir in the sediments, it is a significant factor. As a result of the calculation, the residence time of nitrogen fertilizer in the fishery ground is 200 years based on present fishery activities. Similar calculations can be performed for other substances such as phosphate and trace metals. It may be that some organo-metallic compounds are more important than nitrogen in controlling the fertility of the ocean.

Discussion

Intensive commercial fishery activities have occurred along the edge of the continental shelf in recent years. This fishery is associated with the water current regime, warming of the surface waters, availability of nutrients, and photosynthetic activity. Summer thermocline formation forces stagnation of the upper water, which eventually induces depletion of nutrient substances, especially nitrogen, from the surface layer as photosynthesis takes place. In order to maintain sustained fishery productivity, there must be a means to resupply nutrients. Freshwater runoff, including that of major rivers, and nutrient replenishment from sediments add the needed nutrients to the photic zone. Along the edge of the shelf, where fishery productivity is high, the influence of major river discharge may be investigated by tracing river plumes. This impact may be small because of the great distance existing between major river mouths and the shelf edge. The areal extent and biological effects of river discharge are largely unknown. River inputs are unique in that they are added to the shallow shelf areas as an annual spurt.

In the case of sediment-recycled nutrients, the size of the nutrient reservoir itself and the pathways by which nutrients enter it must be explored. As for the agents that transport nutrients from sediments to seawater, both physical and biological transport mechanisms must be examined. Tidal action, bottom currents, and convective processes are physical mechanisms important to mass transport phenomena. The role of physical mixing in this regard is poorly understood and could well prove to be the dominant process supplying regenerated nutrients in view of the activities of filter-feeding and burrowing organisms. Evaluation of the sediments is integral to chemical study of the Bering Sea, as the possible bottom regime is a source for addition of *recycled* rather than new material.

Any turbidity and cascade currents that are capable of eroding and suspending sediments may have a significant role in replenishing nutrients in seawater. Such events often occur in submarine canyons, which may likely be very fertile regions as evidenced by recent high fish catches occurring frequently over the known submarine canyons along the shelf edge.

Upwelling and upward divergence of deep water from the deep basins of the Bering Sea along and near the edge of the continental shelf are additional mechanisms which resupply needed nutrients into the photic zone. Nutrient-rich water, with a phosphate concentration of over 3 μM/kg and nitrate of over 40 μM/kg exists at a depth of 400 m in the Bering Sea.

A technique has recently been devised using the rate of CO_2 exchange to the atmosphere to estimate the rate of supply of nutrients to the euphotic zone (Kelley et al. 1973), which may offer a valuable means of establishing an input term for nutrients entering the Bering Sea as a result of vertical mixing processes within and near the Aleutian island passes.

RECOMMENDED RESEARCH GOALS:

1. *Evaluation of seasonal and spatial distribution of source materials to the Bering Sea*

2. *Evaluation of composition and distribution of chemical species produced by regeneration or decomposition reactions in interstitial waters*

3. *Evaluation of the seasonal course and vertical distribution of carbon dioxide in the sea to aid in the determination of areas of high primary productivity*

   : : Knowledge of the extent of *high* surface CO_2 partial pressures and its rate of exchange across the sea surface may allow for an evaluation of the magnitude of vertical nutrient transport.
   : : *Low* partial pressures of CO_2 may be used to infer the level of primary productivity, and an assessment of these areas and data on air-sea surface exchange should be used in assisting in primary productivity measurements.

4. *Emphasis on the phenomena and occurrence of areas of upwelling and significant vertical mixing.* Areas of the sea which exhibit such characteristics are regions of high biological activity and of potential fishery resources.

5. *Detailed investigations of the chemical composition of sea ice and its importance to the quality of sea water*

6. *Calculations of material balance for predictive model development* with the acquisition of high quality seasonal data on the distribution of chemical species in the Bering Sea.

6

geological oceanography

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Scope

In a study of renewable resources in the Bering Sea, geological investigations can attempt to supply answers to questions concerning the nature of the nutrient reservoir in the bottom sediments, the nature and stability of the substrate for benthic organisms, the long-term historical baselines for certain variables in the oceanographic regimen, and the nature of the non-renewable resources and their possible utilization conflict with renewable resources. Examination of each of these problems can be well defined by geologic concepts and is within the limits of modern technology.

The distribution of several nutrients in sediments (C, N, and Si, for example) is known to be associated with grain size of the sediment. Consequently, knowledge obtained of sediment transport and the sediment budget can be pertinent in studying the recycling of nutrients from the sediments.

The distribution of benthic organisms is known to be associated with sediment texture as well as with the availability and nature of nutrients. Therefore, knowledge of the stability of the textural distribution (which is derived from a study of sediment composition), transport, and the sediment budget is fundamental to an understanding of the distribution of benthic organisms. Estimating the restorative power of bottom sediment disturbed by human activity also depends upon an understanding of the sediment budget.

Even without the intervention of human activity in the Bering Sea in any form, the environment of this region in the recent past has undergone dynamic changes, particularly in response to climate related sea-level fluctuations. Only by means of a stratigraphic study of the sediments that have accumulated over the past few thousand years can a truly long-term baseline be determined, at least for those processes in the oceanographic regime that produce preservable responses in the sediments. The near-bottom currents, for instance, are a process having a preservable response to direction of net flow.

Assessment

The most promising non-renewable resources of the Bering Sea shelf are petroleum, natural gas, and certain heavy metals. Although the heavy metal resources may be areally restricted to near shore, the petroleum and natural gas resources may be expected in the same areas of the shelf as the greatest concentration of renewable resources, again in part for the reason of long-term high productivity. Conflicts between utilization of the renewable resources may be expected. Geologic studies are requisite to developing the non-renewable resources and can provide information to help resolve the expected conflicts in resource utilization.

Discussion

Nutrients and the sediment budget

Productivity in marine waters is mostly dependent upon the cycling of carbon, silicon, phosphorus, and nitrogen Some of these nutrients have important sources in the sediments, and their pathways in the marine environment are controlled to an extent by sediment source and movement. Important sources of nutrients may include the suspended and dissolved loads of rivers, the suspended load in sea ice; the suspended load in the atmosphere; recycling from coastal lagoons and from mobilized pore water of outer shelf sediments; deep water upwelling from the Aleutian Basin; and the North Pacific water entering through passes of the Aleutian Islands.

The listing of these sources is not meant to imply an ordering by importance, for upwelling is probably the most significant contribution; rather, the intention is to identify the sources involving sediments. Although some measurements should be made of the suspended load entering through the Aleutian passes and of that supplied by upwelling, the other four sources cited above are probably more important to sediment studies.

River and coastal study

River discharge into the Bering Sea plays a significant role in the formation of water masses and in the circulation of the surface water on the continental shelf. The river water carries large amounts of sediment in suspension that are retained in the freshwater plume in the marine environment. These plumes can cover large areas of the shelf water; the Yukon River plume, for example, covers more than 10,000 km^2. The Yukon River alone discharges detritus into the Bering Sea at an annual rate one-third that of the Mississippi River.

The discharge occurs mainly during the summer months and coincides with the summer phytoplankton bloom. Productivity, particularly near the mouths of the major rivers, is related to the nature and amount of detritus present. Sharma et al. (1972, p. 2005) have shown that particulate organic carbon is supplied by the rivers in Bristol Bay and that it occurs most abundantly with the clay-size sediment. This organic carbon may be an important factor in determining the population density. In addition, the sediment in suspension may attenuate the light for the benthic fauna or its deposition may tend to bury the benthic organisms. On the other hand, detritus-feeding species may proliferate in regions of high sedimentation.

The variety of effects that the introduction of river sediment into the marine environment may have on the productivity and the benthic fauna calls for a detailed investigation of river sediment carried as suspended load and bed load. This investigation should be coordinated with a separate examination of the dissolved load of the rivers.

Measurements are needed of the three loads in the important rivers, such as the Yukon and Kuskokwim, for times of significant river flow. Furthermore, the role of coastal lagoons as sources or sinks of nutrients can be evaluated by similar measurements, with perhaps more emphasis on the nutrients, at the inlets and outlets of the lagoons. The coastal pathways of dispersal of the river and lagoon suspended loads with their associated nutrients may be defined near the coast by ERTS (Environmental Resource Technology Satellite) imagery. Not only can the distribution of sediments in the surface water and the extent of the plumes be studied by use of ERTS imagery, but quantitative estimates of the concentration of suspended sediment and of sediment transport rates can be made by obtaining ground truth data in the field and by density slicing of ERTS imagery (Sharma et al. 1973).

Sediment transport by water

The pathways in the shelf sea of transport of continentally-derived organic detritus and of fine-grained mineral particles are unknown. Also unknown is the nature of the processes associated with the transport and deposition of these materials. Present knowledge suggests that material derived from the Yukon River is transported northward away from the central and southern Bering Sea. Therefore, the large quantities of Yukon detritus are not available to the nutrient budget of the shelf break region. Little is known about the fate of detritus introduced by the Kuskokwim and other rivers along the southeastern shore. Moreover, approximately 1.5×10^{14} m^3 of Pacific water, with an average suspended matter concentration of 2 mg/liter, enters the Bering Sea annually through passes in the Aleutian Islands. The fate of these sediments and their influence on the Bering Sea productivity also are unknown.

Therefore, measurements are needed of the transport processes of the suspended load and bed load on the shelf. The suspended load is probably more important for transport of nutrients associated with the sediment, but the bed load transport will affect the recycling of the nutrients from the deposit into the water column. The sediment movement in the water column is of particular interest and significance due to the turbulence and mobility of the Bering Sea waters.

A systematic program of measuring the rates of sediment transport with a goal of estimating the sediment budget will require measurements at sites distributed across the shelf. This pattern is necessary because the shelf may be considered as lying between a sediment *source* at the shore and a sediment *sink* at the shelf break.

Although emphasis should be placed upon sediment transport measurements on the shelf, the possible sediment sink beyond the shelf – on the continental slope – should not be ignored. This slope is indented with numerous canyons that have served as major dispersal routes to the deep sea floor for shelf sediments in the past and that today are sites of upwelling waters carrying nutrients and possibly sediments to near the surface. It has been suggested that turbidity currents capable of eroding and resuspending sediments may have a significant role in replenishing nutrients to sea water. Upwelling may carry these nutrients upward to produce fertile areas in the vicinity of canyon heads. Turbidity currents, however, require a sediment source, and the little information available at present suggests that sedimentation rates on the upper slope are quite low. Before turbidity currents can be considered an important process contributing to the nutrient cycle, we must determine a source of and supply route for sediment available for deposition in the canyon heads.

Sediment transport by ice

The presence of seasonal ice is a unique and nutritionally important parameter in the Bering Sea ecosystem. The structure and distribution of the sea ice has been well studied, and its role in the ecology of sea mammals is well known. An algal bloom that develops on the underside of the ice contributes to the remarkably high productivity of the Bering Sea. However, several vital interactions between sea ice and sediments have been inadequately studied.

Layers of fine-grained sediment have been observed in the sea ice (Sharma et al. 1971). The source of this sediment, however, is unknown. Suspended sediment may be incorporated episodically as the ice thickens by freezing downward. Or windborne sediment from the neighboring land may be deposited on the ice and then covered by snow. The means by which the sediment is incorporated into the ice should be identified.

Also to be identified is the role that the frozen layers of sediment play in supporting the spring algal bloom. The effect of the release of the frozen sediment to sea-water, including a possible increase in the productivity, needs further study. This investigation can be conducted near the edge of the sea ice during spring. Once the sediment has reached the bottom after being released from the ice, the question remains of whether its addition to the bottom sediment provides an ice transport modification to the distribution or properties of the bottom sediment. The deposition of fine-grained sediment from sea ice needs to be studied.

The formation of sea ice, its movement and the extent of sea ice cover in the Bering Sea can be studied by ERTS-A imagery. The distribution and migration of certain marine mammals and other taxa are related to sea ice, and the study of sea ice movement should be fruitful for determining mammalian biomass distribution in the Bering Sea. A similar study is currently underway in the Chukchi Sea, conducted jointly by the Alaska State Department of Fish and Game and the Institute of Marine Science, University of Alaska, as part of the ERTS-1 program sponsored by NASA (Sharma et al. 1973). By combining the ERTS imagery study with sampling of the sediment in the ice, it may be possible to identify the source of some of the sediments. The sampling alone would provide information on the nature and amount of sediment present and should be useful in studies of the effect of the sediment on the physical character of the sea ice.

Finally, the ice mass itself is important as a geologic agent, apart from being a transporting process for sediment. Studies are needed of processes at the bottom of the sea ice when the ice comes near the sea floor. To what extent do grounded pressure ridges plow the bottom? Does sea ice play a significant role in resuspending bottom sediments and in recycling nutrients? In what areas are these effects felt, and how intense is the impact?

Sediment transport by air

The transport of sediment in the atmosphere should be examined in two parts: one dealing with the transport of volcanic material from the adjacent volcanic regions, and the second dealing with the transport of non-volcanic dust from the large adjacent land masses. An estimate is needed of the quantity and composition of windborne sediment supplied to the Bering Sea, and it should be based upon measurements from aircraft, as well as from land and ships. The episodic nature of volcanic phenomena, of course, poses difficulties for a sampling program. The windborne contribution of sediment and nutrients, however, is probably minor.

Recycling of nutrients from the sediments

The sediment pore waters generally contain 300 times more dissolved nutrients than is available in seawater. Since the source of the dissolved ions in pore water is minerals in the solid phase, determination of the mineral distribution and abundance will be required to properly understand the chemistry of the sediment pore water. Nutrients may be recycled from the sediments back into the water column by molecular diffusion or, more likely, by physically or biologically controlled mixing. For the physically controlled mixing, storms may be the most important agent. Lisitsyn (1966) discusses measurements of suspended sediment near the bottom that can be best interpreted as indicating roiling by storms of the bottom sediment on the Bering Shelf to depths of at least 90 m. Storms on this shelf may occur twice monthly for long-term periods. To assess the role of storms in mobilizing sediment pore water, nutrient concentrations must be measured in the bottom water and pore water frequently enough to insure acquisition of data for pre-storm and post-storm periods. In addition, since no measurements are available of the depth below the bottom to which the roiling occurs, some experiments should be planned with this information as the goal. A knowledge of how much of the sediment column is resuspended will be vital to construction of a sediment budget.

The study of biologically controlled mixing will be discussed in more detail later, but one point should be made here. An important source of nutrients that might have been overlooked occurs in the sediment layers beneath the surficial sediments. The depth of natural stirring of the sediments beneath the outer shelf is not known, but such stirring must be an important consideration in a study of nutrient cycling. Deep trawling and its attendant disturbance of the sediments might tap deeper nutrient supplies. It has been postulated that the Yukon River flowed southward across the Bering Sea shelf during the period of the last sea level lowering and subsequent transgression. If this is true, then high sedimentation rates and significant discharge of nutrients could have produced a large sediment reservoir of nutrients only shallowly buried near the shelf edge. If these nutrients are being released by trawling, they must be included in any budgets and considered a non-renewable resource.

The substrate and the sediment budget

The distribution of benthic organisms is generally related to the nature of the substrate. The stability of the substrate can therefore be expected to control these distributions to some extent. For example, if sediment in an area of the shelf is becoming coarser in mean grain size due to winnowing of relict sediment, then the distribution of benthic organisms may be expected to change. Or when the progradation of fine-grained sediment reaches an area of coarser sediment and begins to cover it, the distribution of benthic organisms may also be expected to change. The stability of the substrate is determined largely by the sediment budget. Also, the restoration of perturbations in the substrate by extreme conditions, including human activity, depends upon the sediment budget. For example, if trawling were to change the sorting of the sediment by disturbing the bottom, the restoration of this perturbation would depend upon the sediment budget.

An understanding of the processes by which organisms influence sediments and knowledge of the rates at which these processes act are required for an understanding of the dynamics of the substrate distribution and rates of nutrient recycling from the sea bed.

Benthic communities are strongly associated with particular substrates on the Bering Sea shelf. It is likely, however, that to some degree the organisms themselves control the characteristics of their substrates. Bottom fish and some infauna physically stir the upper layer of sediment, throwing it into suspension. In the presence of a bottom current, the finer biologically suspended particles will be transported readily while coarser particles lag behind. This may be a mechanism for maintaining the substrate grain size and sorting within a range that is suitable for the organisms. Some kinds of organisms tend to bind sediment particles together with mucous secretions or to form sand-sized fecal pellets from silt- and clay-sized material, thus affecting its ability to be transported. If these processes are important in influencing characteristics of the substrate and if the standing stocks of organisms are sufficiently large to appear important, then the possibility of irreversible and deleterious effects on the substrate may be a factor in lowering the biomass through fishing operations. Could the substrate become altered sufficiently to retard restocking?

The rate at which the surface sediment is turned over by benthic stirring may be an important consideration in the rate of nutrient recycling from the sea floor.

If the rate at which sediments are turned over leaves an imprint in lithologic characteristics, it may be possible to hindcast these rates by examining the sedimentary record in cores. This may be important in considering natural fluctuations in renewable resources over periods of hundreds to thousands of years.

Delineation of sedimentary regimes in the Bering Sea should be expected to reflect the benthic species distribution. Except for the area along the outer shelf, most of the sedimentary regimes have already been defined by bottom sediment analysis: for the western Bering Sea by Lisitsyn (1966), the central by Knebel (1972), the northernmost by McManus et al. (in press), the southeastern by Askren (1972), and Bristol Bay by Sharma et al. (1972). A summary review of the bottom sediments on the Bering shelf is given by Sharma (1974a, b). The bottom sediments on the outer continental shelf and the continental slope should be examined for particle size, mineral composition, and chemical composition, in order to complete the reconnaissance routine study of shelf and slope sediments.

Determination of mineral differentiation in sediments is extremely useful in defining regions of longshore currents and high energy environments, both at present and in the geologic past. These regions contain deposits of heavy minerals and potentially toxic metals. The influence of concentrations of these minerals on the biota of the Bering Sea needs scrutiny. The potential hazard of biological poisoning remains omnipresent because of the location of a mineralized zone along the coast. In view of the world-wide shortage of mineral ores, the mines along the coast may be reactivated. The effect of adding metals such as mercury to the seawater may be locally disastrous to biota. The coastal zone of heavy minerals should be defined and its environment examined.

Beyond these routine analyses lies the need to understand the bed load transport and biologic reworking of the bottom sediments. In addition, information is needed on the effect of human activity. Fishing activities must have environmental effects beyond the direct effects of reducing the fished populations. It is important to intensely study the sedimentology of a heavily fished bottom region and compare the results with those from an area with a similar sedimentary environment free of a significant fisheries. It would also be important to purposefully and systematically fish the control area as if ground fish were present, in order to determine the fishing effects on the sediment. The importance lies in the possibility that fishing may have significant impact on the sedimentary environment which in turn will influence the substrate type and composition. The fishing operation will put a layer of bottom sediment into suspension. This sediment will be advected to a new bottom position by the bottom current. If the sediment is disturbed to a greater than normal (natural) depth below the sea floor, an artificial surface could result that has a significantly different grain size. This in turn might have a significant effect on the amount and type of infauna, nutrient cycling and bottom stability. Thus, an experiment should be made to study the effects of fishing operations on the bottom sediment.

The sediment budget

To determine the sediment budget, we need to know several sediment budgets, one for each type of particle. For simplification we can group particles genetically: for example, non-shelled organic particles, shelled organic particles, terrigenous sand, terrigenous silt, terrigenous clay, and volcanic silt. This classification is only illustrative, however. For each group of particles, information is needed on processes affecting them and on the rates of these processes. The rates may differ between groups and may differ with time. Thus it is important to consider the groups separately and to obtain measurements of the rates under various conditions of the environment. The rates to be measured comprise rates of supply, transport, sedimentation, dissolution (decomposition), resuspension, and accumulation.

Particles are supplied to the shelf by rivers, shore erosion, winds, ice, and organisms. Each process supplies different particles, different combinations of particles, or different amounts of various particles. These particles are then transported by the seawater, at the surface or in the water column, by ice or by wind. The rate of sedimentation is a measure of the arrival of particles on the sea floor and obviously changes with fluctuating rates of supply or transport. During residency in the water column or after sedimentation, some particles may be partially or totally removed by dissolution or decomposition. This process is particularly significant in affecting the organic particles. Also, particles on the bottom may be resuspended by physically or biologically controlled mixing and thereby be retransported for some distance before settling back to the bottom. Finally, with or without resuspension, the sediment accumulates at some rate. The episodic nature of the other rates may well result in an episodic rate of accumulation, although this may be unmeasurable if the resolution of the measuring technique is much greater than that of the techniques for measuring the other rates.

The measurements of these rates must be coordinated with the measurements of the other physical, chemical, and biological variables in the water column. The rate, even of accumulation, should be based on an appropriately short time scale. It is apparent, therefore, that in addition to underway measurements on board ship and airplane and to measurements on station, some bottom-mounted monitoring devices must be included, similar to those of Sternberg and Creager (1965). These devices should at least be able to operate seasonally, if not annually. The minimal types of measurements needed are listed at the end of this chapter.

The historical record preserved in the sediments

Study of the long-term historical record contained in the sediments is an essential part of an effort to estimate the sedimentary and nutrient budget. Stratigraphic study of the sediments provides the basis for estimating rates of accumulation and dispersal paths of different components of the sediment, over a long period of time. In areas of net accumulation, a portion of the sediment and its entrained nutrients is removed more or less permanently from the ecosystem. The sediment body then becomes a reservoir of nutrients available for recycling by bioturbation, human disturbance, or geologic events. Stratigraphic study of the sediments is thus essential to complete the equation that involves input of sediment and nutrients from terrestrial and external oceanographic sources, export of sediment and their nutrients through the straits, use of sediment and nutrients by the biota, and loss of sediment nutrients by permanent burial.

Sedimentological and paleobiological study of the stratigraphic record also provides long-term, time-integrated information on direction and intensity of sediment transport by paleoenvironments, biostratigraphy and other oceanographic processes, and thus provides an independent test of the significance of short-term synoptic oceanographic studies.

Human intervention can affect the Bering Sea ecosystem quite seriously, even catastrophically. Even without the impact of human activity, however, the ecosystem changes with time and *has* changed, drastically, in ancient times. For example, all except the outermost fringe of the continental shelf of the Bering Sea was emergent as dry land only 18,000 years ago. The sea level rose slowly, and the present configuration of Bering Sea with its attendant circulation and sea-ice regime did not come into existence until about 6000 years ago. The sediment body retains a record of many components of the ecosystem and of temperature and water circulation regimes quite different from those of the present time. Paleobiological, paleooceanographic and paleoclimatic records of preserved sediments should provide us with insights into the long-term variability of the ecosystem, given the present configuration of the Bering Sea, and of the effects of the different configuration that existed when the sea level was lower. It may even be possible to derive crude estimates of paleo-productivity, by careful quantitative study of the biogenous component of the sediments. We may find evidence in the stratigraphic record of past catastrophes and of the rate of the ensuing recovery. Studies of this nature will provide us with information upon which to base conclusions concerning the long-term stability of the Bering Sea ecosystem, given a continuation of the present climate, or the possible effects of a climatic change, as well as of the possible effects of human exploitation. Thus, a comprehensive study should be made of the sedimentologic history of the Bering shelf since the beginning of the last rise in sea level.

Assessment

Non-renewable resources

Investigators studying renewable resources on the Bering shelf should be cognizant of the non-renewable resources and be alert to possible conflicts in resource utilization. To this extent, the non-renewable resources should also be considered. The most promising non-renewable resources are hydrocarbons and heavy metals.

Hydrocarbons

The accumulation of hydrocarbons requires source beds, reservoirs, and traps. The source beds are sediments rich in organic remains, and although petroleum seems to be supported only by marine organic deposits, natural gas can also be derived from continental sediments. The reservoirs are porous or cavernous layers which must be sealed off by a barrier to the fluid, thus trapping the hydrocarbons in the reservoir. In general, thick sedimentary sequences that are only mildly deformed satisfy the requirements for hydrocarbon accumulation. Deltas and other areas of long-continued high organic productivity are especially promising sites of accumulation.

Probably 75 percent of the Bering shelf holds some likelihood of hydrocarbon accumulation, and some areas of the shelf are extremely promising. The most promising areas are the sedimentary basins near the margin on the outer shelf and the Bristol Bay basin. It is not entirely coincidental that these sites are also the best areas for fisheries. The high organic productivity that is a creative element to both resources has a long history in these areas.

The outer continental shelf basins are small, fault-bounded basins with 1-2 km of Oligocene to Recent deposits, mainly consisting of diatomite and diatomaceous sand, with some conglomerate. The organic remains are abundant and the reservoirs are abundant. But the presence of traps is not yet established.

The large Bristol Basin contains several kilometers of terrigenous and volcanigenic sediments. Evidently it has been the site of a shallow marine embayment throughout much of the Tertiary. As for the outer shelf basins, however, the presence of traps has not been established.

From the Pribilof Islands to St. Lawrence Island, the shelf is formed by a thick prism of sediments whose source is not clearly defined. Presumably, this part of the shelf was flooded early in the shelf history, perhaps late Oligocene or early Miocene, which would have produced marine source beds in the lower part of the sedimentary section. In addition, the Kuskokwim River could have been a major source of sediment prior to the middle Miocene, and the Yukon River may have contributed sediment here after the middle of the Miocene. To be sure, not enough information is available on the paleogeography to infer much about the reservoir beds, but ancient river channel-fills and beach sediments are probably present. Below this section are gently folded beds likely of Cretaceous age and probably largely of non-marine origin. The possibility exists of very large volumes of hydrocarbons, particularly natural gas, being present beneath this part of the shelf.

The Norton Basin, beneath Norton Sound, was inundated during the late Miocene but probably not much earlier. Since the basin was evidently receiving continental sediments from late Oligocene, however, reservoir rocks should be common, mainly as river-channel sands, although lake deposits may be present. The Yukon River has been a major source of sediment since the middle Miocene. Large sources of natural gas are likely present here, but the existence of petroleum is doubtful.

Drilling and production in Bristol Bay and on the outer continental shelf pose a potential disruption of fishery operation hazards through navigation and trawling, potential blow-outs, and oil spills incurred during loading operations. These difficulties, however, may not be as severe as the impact on the biota itself. Large oil spills or blow-outs would have a temporary but potentially severe effect, especially on birds and marine mammals.

Drilling and production farther north would have little effect upon the fishery, although potential deleterious effects on the mammals and birds is possible. Moreover, ice increases the hazard to installations and ships and must thus be considered as increasing the likelihood of a spill.

Finally, it should be noted that the position of the international boundary on the shelf has never been adjudicated. Since there is a real possibility of locating an oil field in the shadow zone or astride the boundary, the question arises as to implications of this on the division and utilization of other resources on the shelf.

Heavy metals

The possible occurrence of gold, platinum, and tin placers on the Bering shelf is well-known. Exploration has shown, however, that almost all such placers will occur in the nearshore zone, generally less than 5 km from shore. Off the southwestern Seward Peninsula, they may be found 10 km from shore. Thus far the results of placer exploration have been disappointing. The only significant discoveries are a rich but small, submerged, stream placer (gold) off Bluff and much larger, low grade gold deposits on the sea floor off Nome. Other gold placers may be found, but they probably will not be large. The search for tin in and near the Bering Strait and for platinum in and near Goodnews Bay has yet to yield more than minor occurrences.

Sea-floor mining for gold, tin, or platinum will be extremely disruptive to the benthic fauna. Yet, the operations will help to recycle nutrients by churning up the bottom sediment. In any case, the areas affected will be small.

There is some possibility of finding other types of placers on the shelf: zircon, rutile, ilmenite, or magnetite. If present, these placers are likely to be more or less exposed over large areas. Likely, development would be in embayments with intense tidal currents (such as Kvichak, Nushagak, or Kuskokwim bays) or in the current-swept northernmost Bering Sea.

RECOMMENDED RESEARCH GOALS:

Geological data necessary for an understanding of the renewal resources of the Bering Sea continental shelf are: 1) the nature of the reservoir of nutrients in the bottom sediments, 2) the stability of the substrate for benthic organisms, 3) the long-term historical baselines for comparison with typical short-term measurements of the oceanographic regime, and 4) the nature of non-renewable resources and the likelihood of conflicts in resource utilization. The first two contributions can be made by studying the processes which are eroding, transporting, and depositing the sedimentary particles on the shelf; by measuring rates of these processes; and by estimating a sediment budget for each type of sedimentary particle. In order to determine the budget for each type of particle, the particles themselves have to be analyzed. The study of the sediment budget on the Bering shelf should be assigned the highest priority of geologic study. The study of the sediment budget on the continental slope is separate but closely related.

In order to provide a historical baseline of sufficient duration to evaluate the temporal significance of some measurements of the oceanographic regime , a stratigraphic study should be made of the sediments deposited since the beginning of the last rise in sea level. The stratigraphic study described here should share the highest priority with the study of the shelf sediment budget.

The exploitation of non-renewable resources in the continental margin may have some direct effects upon the established utilization of the renewable resources. While a study of the non-renewable resources is not rated a high priority in this evaluation, their active exploration and exploitation must continue and accelerate. The future possibility of conflicts in resource utilization should be underscored now.

1. *Underway measurements and observations*

: : Side-scan sonar, surface sediment distribution; 4 kHz seismic reflection, thickness of recent sediment; sampling suspended particles, concentration and composition

2. *On site studies*

: : Suspended load in the water column from the surface to 1 m from bottom: light transmission or scattering, vertical profile; core of transgressive sequence, vibrating or piston corer; hydraulically-damped core, for surface sediments; box core, for sediment-benthic fauna relationship, bottom photographs

3. Bottom-mounted arrays

: : Current meters for profile of near-bottom currents; pressure recorders for waves; bottom photographs; light transmission or scattering measurements for vertical profile near bottom; suspended sediment samplers for vertical profile determinations; bulk density or porosity measurements; autoanalyzer assays; temperature, salinity, and oxygen measurements

4. Ice study

: : Samples of frozen sediment; ERTS imagery; divers

5. Atmospheric dust

: : Filter sampling and nephelometry by airplane, ship and on land

6. River and coastal study

: : Samples of, suspended, dissolved, and bed load; measurements of water discharge; ERTS imagery.

7

physical oceanography and air-sea interaction

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Scope

Along with its many unique features covering all aspects of oceanographic disciplines, the Bering Sea plays a key role in influencing weather and climate and in influencing the water masses of the North Pacific Ocean. Its surface is the North Pacific environmental boundary on the polar side of the westerlies, but, because it has a highly variable seasonal ice cover largely confined to the shelf, there is a marked seasonally variable boundary effect. Reid's (1965) charts depicting North Pacific intermediate water property distributions show a direct connection with the Bering Sea, thus suggesting that this water mass may be in part manufactured there and fed to the North Pacific – particularly from the two largest and westernmost passes through the Aleutian Islands.

Within the sea, certain physical characteristics provide unique opportunities to study basic physical oceanographic processes. On the extremely broad continental shelf, second in the world ocean only to the arctic continental shelf of the Chukchi, East-Siberian and Laptev seas, many aspects of shelf dynamics could be readily studied in a relatively accessible location. Also, as the shelf is seasonally ice-covered, the role of ice on all aspects of shelf oceanography could be best studied here.

Upwelling

Upwelling occurs along significant portions of the continental shelf edge and is readily identified by the prevailing oceanographic parameters. This phenomenon seems to occur in discrete locations, related to bathymetric effects, so non-upwelled areas offer adjacent regions for "control" study. Significant "upwelling" also occurs north of certain eastern Aleutian island passes, but this appears to be of a dynamically different character than that occurring along the shelf edge. Both types of upwelling are obviously enormously important to, and may be the primary reason why, some of the highest values of primary production ever measured in the world ocean were from the outer Bering Sea shelf. On the other hand, it seems significant to note that the oceanographic community in general appears to be unaware of these facts concerning the Bering Sea; in recent overview papers on upwelling (e.g., Smith 1968; Margalef 1971), the Bering Sea is ignored.

Meteorology

An especially important physical feature of the Bering Sea which is as yet largely unexplored appears to be its influence on the weather and climatology of the North Pacific Ocean. In terms of thermal exchange with the atmosphere, an ice-covered surface takes on many of the characteristics of a continental area; hence, in effect, the polar side of the North Pacific westerlies appears as a land-type surface over the whole continental shelf area south to the Pribilof Islands in winter, but in summer the surface is open water to north of the Bering Strait. It would seem, intuitively, that the position and strength of the Aleutian Low and the major cyclone track of the North Pacific (ENE parallel to the Aleutian Islands) must be predominantly governed by these particular seasonally variable conditions occurring in the Bering Sea.

Assessment

Because the Bering Sea contains biological and geological resources of enormous importance to man, thorough understanding of the physical oceanographic conditions operating in the sea is essential to rational utilization of these resources. Focal subjects must include studies of the circulation and its time-variability which governs the supply and distribution of nutrient elements, the formation and circulation of specific water masses such as the very cold (less than -1 degree C) shelf bottom water that plays a key biological role in constraining the distribution of bottom flora and fauna, the location and strength of the strong tidal currents (particularly over the shelf) which strongly influence sediment distribution, and the nature and movement of sea ice and its relationship to surface circulation and winds, which may prove to be a limiting factor in commercial exploitation.

We have tried to identify all important physical oceanographic problems of the Bering Sea in the light of our present knowledge and have classified them generically as key problem topics. Below, each of these is discussed in more detail, together with proposed oceanographic studies aimed toward solutions which utilize all potentially available resources.

General circulation

The Bering Sea naturally divides into two regimes — shelf and deep basin. The shelf regime occupies approximately the eastern and northern third of the sea, while the central and western sea has typical oceanic depths (3700-4000 m). The basin floors are very flat, and the depths grade very slightly from shallower (3700 m) in the eastern central basin to deeper (4000 m) in the southwest. Most significant, however, is the presence of ridges such as Olyutorskii and Bowers, which subdivide the sea into sub-basins. This feature added to the weak baroclinicity typical of the Bering Sea leads to a strongly topographically influenced circulation.

Shelf regime. The circulation over the shelf *north* of St. Lawrence Island is reasonably well-known. Details of the circulation, including transport through the Bering Strait and seasonal variations, are described in a monograph by Coachman et al. (in press). In contrast, the circulation over the shelf *south* of St. Lawrence Island must be considered essentially unknown. The water boundary condition are: on the *east* the large, seasonally variable flux of freshwater from Alaska, partially focused as major river flows from the Yukon and Kuskokwim; on the *west* the Transverse Current (Arsen'ev 1967) follows the continental slope from Bristol Bay in the southeast to Cape Navarin in the northwest. The positive existence of this current has now been established by the results (unpublished) of cruise TT-071 *T. G. Thompson*, July 1972, which included drogue measurements in two locations of the flow over the continental slope.

No comprehensive survey over the continental shelf has ever been made from which even a gross circulation pattern can be interpreted. All work has been piecemeal, and perhaps Bristol Bay is better known than the rest of the shelf; the only current measurements available from the shelf area are from Bristol Bay (Hebard 1961), with the exception of a recent series of 10 anchored current stations between St. Lawrence and St. Matthew islands (TT-085, *T. G. Thompson*, October 1973). For the whole shelf area, course distribution patterns of water properties have been published from compilation of over 1 year's data (e.g., Ohtani 1973).

We conclude that the lack of information at present precludes even the crudest quasi-synoptic view of what the overall shelf circulation might be like. The generality can be made that there must be a net south-to-north movement, as the flux of 1-2 Sv north through Bering Strait essentially bleeds off on the average about 1 Sv of continental shelf water. This is compensated in part by the influx into the southernmost shelf areas of Pacific surface-layer water, which most likely is largely provided by transport through the eastern Aleutian passes. This situation will only be rectified by a series of sufficiently detailed and quasi-synoptic surveys in context of the obvious seasonal variations. Circulation patterns can be primarily interpreted by applying distribution of variables theory, but some reference current measurements are required to establish the fluxes.

Deep basin circulation. Circulation in the deep basin is better known than that over the shelf. The Soviet expeditions of 1958-1961, which included the only attempt at a winter survey, were too sketchy in essence to clearly define the circulation, in part because of its very complex nature. As shown also by the numerical study of J. A. Galt (unpublished), topographic influence on the circulation might be strong. Galt's results show that the wind stress torque tends to drive a cyclonic gyre circulation, but the topographic influences cause the gyres to subdivide into a series of gyres. However, no available data allow a clear and unambiguous verification of these. It has also been established that wind stress torque in winter is an order of magnitude greater than in summer (Hughes et al. 1974), but the response of the deep basin circulation to this variation in primary driving force is not known. The deep circulation has never been studied.

We conclude that circulation in the deep basins is not sufficiently known to allow even reasonable estimates of the advection of such properties as nutrients. A recently completed survey (TT-085, *T. G. Thompson*, October-November 1973) occupied 160 STD stations over the central and western deep basin, but the data remain to be analyzed. Detailed descriptive surveys are required before further progress can be made in either understanding any of the major oceanographic problems of the Bering Sea and its connection with the North Pacific or planning of specific experiments addressed towards any of these questions.

Continental shelf break and slope region. Dividing the shelf and deep basin regimes, the Transverse Current provides a dynamic boundary along this edge, across which fluxes of properties occur both onto and off of the shelf. These processes must be of fundamental importance to many phenomena in the sea, and surveys to properly define the circulation would also be used to adequately locate the sites where major transverse fluxes may occur.

Shelf tides. Tidal motion on the continental shelf is significant, and, in particular locations, large tidal current amplitudes dominate the flow field. However, published tidal charts of the shelf are in conflict, and attempts to reconcile the tide wave behavior from published tide data have failed. We believe the shelf is suitable to modern tidal modeling techniques and that tidal studies are of high priority.

Shelf and shelf-edge dynamics

The edge of the continental shelf provides a boundary of considerable importance between the vast, relatively shallow region adjacent to the Alaskan coast and the deep oceanic basins to the southwest Bering Sea. This major demarcation region runs from southeast to northwest, nearly dividing the Bering Sea in half. As with most shelf breaks found in the world ocean, this region can be characterized by a significant change in slope between adjacent waters. In addition, the area also has several excellent examples of large submarine canyons that are found well removed from the influence of coastal boundaries or runoff.

The depth contrast also leads to marked differences in thermal exchange across the air-sea boundary on the shelf vis-a-vis the deep basin, and consequently winter ice formation and intermediate water formation are strongly affected by this boundary. Finally, the combined interaction of the currents and bathymetry (particularly in the vicinity of the submarine canyons) results in a vertical transport of the nutrients and consequent high productivity that support a substantial fisheries industry, which is also concentrated in the vicinity of this major bathymetric feature.

In order to elucidate the dynamics of this highly significant region, studies will have to be designed to investigate a number of key processes or features. In particular: (1) The nature of the current interface between the transverse flow along the continental slope (Transverse Current) and the waters over the shelf must be documented and described. (2) Dominant length and time-scales of shelf and edge waves found in the vicinity of the shelf break should be measured and studies directed at the proper parameterization of their contribution to the cross-isobath nutrient transfer. (3) The details of circulation in the vicinity of major submarine canyons should be investigated and bathymetric constraints on internal waves, tidal currents and thermohaline-driven flow described in sufficient detail to identify key advection and mixing of oceanographic constituents. (4) In addition, water mass characteristics across the area of the shelf break should be documented in enough detail to indicate the effect of this feature on the distribution and flow of intermediate waters formed on the shelf and found throughout a significant portion of the deeper basins.

Inflow through eastern passes

Flow into the Bering Sea through the eastern Aleutian island passes originates from the Alaskan Stream, a high velocity (1-2 knots) boundary current transporting relatively warm, dilute water from the periphery of the Gulf of Alaska westward along the south side of the Aleutian-Commander island arc (Favorite 1974). Flow through the passes is dependent on several factors such as sill depth, tidal currents, and pressure gradients in the water column.

Although westward flow south of the island arc extends to depths exceeding 3000 m, sill depths of passes eastward of 180° are only a fraction of this depth. Samalga Pass (169°30 W) is the first opening having a sill depth greater than 100 m, and sill depth greater than 1000 m does not occur until Amchitka Pass (180°). Thus, north-south exchanges through the passes influence primarily the surface layer and to a limited extent only the upper third or fourth of the water column in the eastern Bering Sea.

Tidal flows have been observed in some passes, but most records are only of a few days duration. Surface velocities of 1-5 knots have been observed, the higher velocities being restricted to the narrower passes. Both north and south net flows (over the short intervals of the records) have been recorded at various times (Reed 1971). Arsen'ev (1967) and Ohtani (1973) have shown anticyclonic geostrophic flows encompassing island groups, resulting in net northward flows on the eastern sides of the passes and net southward flows on the western sides. The main feature of all available records is thus the large variability and, as geostrophic approximations are largely invalid in these areas, net fluxes can be determined only from long-term direct current measurements.

Vertical mixing is extensive in the passes, but the distinctive water characteristics of the surface layer (0-150 m) in the eastern Bering Sea can be attributed to a significant northward flow of Alaskan Stream water through eastern Aleutian passes. However, there is considerable controversy concerning actual transport. Leonov (1960) reported that inflow and outflow could occur at the same depth or at various depths in any of the passes. Natarov (1963) estimated that the eastern and central Aleutian passes provided most of the near-surface flow into the Bering Sea, whereas Arsen'ev (1967) concluded that no net exchange occurred in the eastern Aleutian passes and less than a third of the total northward flow occurred in the central Aleutian passes. Direct current observations are required to determine actual transport.

Northward flow into the Bering Sea through the shallow eastern Aleutian passes undergoes not only deformation (horizontal spreading), but there is evidence that this flow also contributes to turbulent upwelling along the north side of the island arc (Kelley et al. 1973). Both of these processes affect conditions and flow in the surface layer of the eastern Bering Sea, and further field work based on model studies is required.

Heat exchange and intermediate water formation

The winter cooling and resulting vertical convection that takes place in the shallower regions of the Bering Sea form an intermediate type water that is advected into the deeper basins and can be identified as a sub-surface temperature minimum at approximately 150 m. Little is actually known about how much of this water is formed annually or the rate at which it spreads throughout the basin. As this layer represents a sink for the heat stored in the upper layer of the Bering Sea, overall heat budget and air-sea transfer studies require a better definition of this water mass than is presently possible. Such critical questions as formation areas, typical residence times and influence of the cold under-layer on the thermal stability of the upper layer should be systematically studied as part of the physical oceanography program.

An important by-product of this study could be a definition of the acoustic environment of the Bering Sea and its time changes. Because the temperature and salinity characteristics in various regions will be well established, it appears possible that the density and sound velocity fields could be interpreted from the measured temperatures.

The Bering Sea ranges from an ice-free sea in the summer to a body of water which is approximately one-half covered with ice in the late winter. Freezing begins near the northern coast and progresses southerly during the winter season, eventually covering most of the shelf area, in some years including Bristol Bay. The ice is broken by leads and polynyi and is advected by winds and currents.

Since ice plays a significant role in many of the physical processes of large-scale air-sea interaction, general circulation, heat exchange and intermediate water formation, the ultimate oceanographic goal is to predict the ice extent and characteristics, its transport, thickness, rate of formation or thawing, and its compactness. This requires incorporating the ice in a model of the atmosphere and ocean. The winds and currents exert a stress on the ice, and heat and mass are transferred to both fluids. The microphysics of these processes are partially understood, but the constitutive relation appropriate for ice on larger scales (50 km or greater) is not well determined. The constitutive relation is essential for a predictive model.

The results of the Arctic Ice Dynamics Joint Experiment (AIDJEX) ought to be very helpful in attacking the problem of ice in the Bering Sea. Even though the AIDJEX study is directed toward ice in the Arctic Ocean, which is multiyear as well as new ice, much of the physics will carry over. Research should be directed towards aspects of Bering Sea ice which are essentially different from that of the Arctic Ocean — namely, the growth, dissolution and structural characteristics and the behavior of the ice front, including its effect on interior ice structure and processes.

Large scale air-sea interaction

The Bering Sea, together with the Gulf of Alaska, is a region of very active generation of storms, particularly in winter. The low pressure associated with this generation is called the *Aleutian Low* by meteorologists. The location and intensity of this low are correlated with the entire northern hemisphere circulation, particularly at high latitudes and over the North American continent. An understanding of the physical processes associated with the location and intensity of the low are therefore very important for predicting weather and climate.

The storms are generated by the passage of very cold and dry continental air out over the Bering Sea and Gulf of Alaska, where large sensible and latent heat transfers to the atmosphere take place due to the large air-sea temperature difference. This heat causes the air column to stretch vertically, leading to convergence near the surface and intensification of the already existing cyclonic vorticity. A storm thus generated is then carried eastward over the North American continent by the mean westerly flow.

Although the broad outlines of large scale air-sea interaction processes are understood, there is a need for much more precise understanding of many aspects of the phenomena. One of these is the nature of the modification of a dry, cold (perhaps -40°C) air mass as it moves over water with surface temperature near 0°C. What is required is the rate of heat exchange as a function of fetch and wind speed and the depth of the modified layer and distribution of properties within it. Some of this understanding may come from air mass modification experiments carried out during the International Field Year for the Great Lakes (IFYGL) and the upcoming Air Mass Transformation Experiment (AMTEX). Theories and models developed from these experiments need to be compared to observations in the Bering Sea and, if necessary, improved or modified.

The influence of the extent of the ice cover on atmospheric circulation, particularly the location of the Aleutian low, needs investigation. The seasonal and year-to-year variability of the ice cover are potentially very important influences on the atmospheric circulation, since the ice acts as an insulator between the air and water, reducing the heat and water vapor exchange by several orders of magnitude. The ice also has a large influence on the radiation balance since its albedo is typically much higher than that of the sea surface. The ice cover then tends to maintain itself by limiting the amount of incoming radiation absorbed.

The response of the ocean to the passage of a storm and the resultant influence on air-sea exchange processes requires study. The wind causes the upper layers of the ocean to diverge beneath a center of atmospheric low pressure. The divergence causes deeper water to be brought to the surface, which may have a greater or lesser temperature than the former surface water. Thus there is the possibility of a feedback, not only by the modification of surface temperatures by large transfers of sensible and latent heat, but by modification due to wind-induced circulation.

The problems of large scale, long period air-sea interaction obviously overlap those of other national and international programs such as the North Pacific Experiment (NORPAX) and the Polar Experiment (POLEX). Every effort should be made to coordinate Bering Sea studies with these and other programs to obtain the maximum possible scientific benefits.

RECOMMENDED RESEARCH GOALS:

I. General circulation studies

: : General surveys of the shelf (south of St. Lawrence Island), shelf edge and deep basin to provide adequate description on which to base more detailed studies

: : Tidal studies on the shelf with initial tide model followed by field program on strategically located land masses to operate for one year

: : Further refinement of existing numerical models as better boundary condition data become available

2. *Shelf and shelf-edge dynamics*
: : Studies specifically designed to include submarine canyon regions and segments of shelf without canyons as controls
: : Bottom drifter study to obtain gross features of bottom water movement over shelf edge area of eastern Bering shelf
: : Studies of dynamics of shelf frontal zones

3. *Eastern Aleutian island passes*
: : Exploratory and feasibility studies as basis for designing proper specific studies of passes in orderly fashion

4. *Heat exchange and intermediate water formation studies*
: : Airborne Expendable Bathythermograph (AXBT) to be deployed as basic tool from U. S. Navy reconnaissance aircraft to cover the entire sea, shelf and deep basin in one or two flights
: : Aircraft to deploy other sensing devices; infrared scanning for sea surface temperatures and possibly drop-sondes to follow air mass modification
: : Monthly flights for one year should be interfaced with NORPAX studies

5. *Dynamics and thermodynamics of sea ice*
: : Physical character of ice cover, surface and bottom morphology and albedo studies
: : Extent of ice cover and changes of time; development of ice budget for Bering Sea through coordination with NASA (National Aeronautics and Space Agency)
: : Physical oceanography associated with ice fronts to start during freezing period and extend through spring, following retreat of ice edge northward
: : Careful study of oceanographic fronts associated with the ice edge, particularly the effects of stress discontinuities and dilution

6. *Large-scale air-sea interaction*
: : Studies, in coordination with NORPAX goals, of air mass modification and mobile ice-boundary influences on the Aleutian low and cyclone tracks
: : Moored buoy studies near the center of the sea with instrumentation to supply standard weather data and sea temperatures as function of depth and time.

8

management and facility requirements

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The scientific programs for investigations of the oceanography of the Bering Sea discussed in the previous sections will require carefully planned management, logistics and data handling systems. While this workshop emphasized the development of a U. S. program for Bering Sea research, the interest of Canada, Japan, Korea, and the USSR in the resources of this region assures that the effort will have high international recognition and provide opportunities for international cooperative programs. It is important that a management system be developed that will provide for a smooth operation within the U. S. community and allow for inclusion of international programs as they develop. Likewise, the needs for logistic support, analytical standardization and data handling require early identification and planning to assure availability of equipment, quality of data and effective information exchange.

Facilities

Research vessels

During the early part of the program (1977), a quasi-synoptic study of the entire Bering Sea will be needed. This study will require the use of 3 ships for a period of 30 days 3 times during the year. Some of these vessels can probably be obtained through cooperation with the Japanese, Koreans, and the USSR. Ships should be requested from UNOLS (University National Oceanographic Laboratory System) as early as possible to carry out this study. Ships of the 160-200 ft class will be needed in order to accommodate the multidisciplinary program required and to serve as suitable platforms for work at sea under rigorous sea-state conditions.

The present fleet of UNOLS ships has little competence for work in the seasonal ice of the Bering Sea. Research in the ice, especially in the marginal ice-covered open water zone, has been stressed by many programs as essential to understanding how the Bering Sea functions.

Part of this requirement, mainly deep ice penetration, can be met with U. S. Coast Guard icebreakers, and requests for these for at least 30 days each year should be made now for work in the winter of 1976 through 1980. This still leaves the high priority requirement for a vessel which can negotiate the marginal ice (30 cm at 3 knots) and rough sea conditions in the seasonal ice zone between November and June of each year to provide the logistics support required for interdisciplinary studies of this dominant feature. Plans for acquisition and operation of such a vessel should proceed with utmost haste. It would appear that special vessel construction will be needed to meet this need.

Data buoys

Some meteorological and oceanographic data buoys deployed in strategic areas of the shelf will be needed. These will provide continuous data to be tied to that obtained by the research vessels deployed for intensive effort for relatively short periods of time. The locations of these buoys should be carefully considered by those people working on circulation and material balance studies. Early use could be made of a buoy system in the Aleutian passes and along the shelf break, particularly in areas of deep submarine canyons resulting in upwelling.

Remote sensing

Satellite imagery from existing ERTS (Earth Resources Technology Satellite) operations will be available for this study. The program is well developed and provides good spatial resolution (100 m), but the satellite passes over a given location only about once every 18 days. Some overlap of adjacent days at high latitudes is realized, however. Extreme cloud cover over the Bering Sea precludes the use of this satellite for temporal studies. The NOAA (National Oceanographic and Atmospheric Administration) 1 and 2 satellites have less resolution (1 km) but provide daily coverage. The recent VHRR (Very High Resolution Radiometry) satellite provides daily coverage and should prove valuable in ice cover and surface circulation studies.

Aircraft of the U. S. Navy or Coast Guard routinely conduct missions in the Bering Sea and may be available for scientific studies on a not-to-interfere basis. Remote sensing aircraft of NASA or of the Scripps Institution of Oceanography may be used to advantage for some observational work, especially in locating upwelled areas, defining current fronts and supplementing data obtained from satellite or data buoys.

Island laboratories

Since Kodiak and Seward are the nearest ports satisfactory as research staging areas for ship deployment in the Bering Sea, there would be considerable advantage to having laboratories established on strategically located islands in the Bering Sea shelf area. There is presently a laboratory for fur seal research on St. George Island and a small biological laboratory on St. Lawrence Island at the town of Gambell which could be used. Additional facilities such as small boats, snow vehicles and laboratory space and facilities will probably be needed; however, the details of these requirements must be worked out as the program develops.

Sampling and analytical equipment

Sampling and analytical devices which give direct deck readout and rapid data display will be needed on the major oceanographic vessels used for Bering Sea research. The changes in the water column in the Bering Sea, particularly on the shelf, are often very dramatic; in order to sample properly, the investigator must have access to pertinent data while he is still in the area and able to follow interesting phenomena. Each ship will require the following standardized equipment: An STD (salinity/temperature/depth) system with rossettes for Niskin sampling bottles; a nephelometer attachment on the STD system; an autoanalyzer with analog-digital converter for nutrient analysis; oxygen, alkalinity, pH and molecular CO_2 measuring devices; a satellite navigator; small in-line computers for analytical data display; and other specialized equipment for specific projects that will be the responsibility of individual investigators.

Intercalibration of all analytical methods used is very important to this program and should be carried out for all possible parameters. Calibration of instruments can probably best be done at the National Regional Calibration Center at Bellevue, Washington.

Data handling center

The storage, processing and dissemination of data should be done at one location, preferably in conjunction with the operational and communication center described below. The data handling center should obtain and format all historical data on the Bering Sea and receive and process all new data as they are obtained to a level that meets the needs of individual investigators. Data transfer by telephone linkage should be a routine operation of this center. The data format used should be standardized for compatibility on an international basis.

The best location for the data handling center would be at the same facility as the management operations, suggested in Alaska at the University campus either at Fairbanks or Anchorage.

Operational center

A center should be established for staging cruises and providing logistic support to all operations in the Bering Sea. This operational center should be located as close to the Bering Sea as possible and yet be near a dependable transportation center to allow easy transfer of personnel and supplies. The Seward Oceanographic Station, operated by the

Institute of Marine Science of the University of Alaska, appears to be the best site for this purpose. Seward is accessible by highway, railroad and air from Anchorage, the supply and communications center of Alaska. Seward is the only suitable harbor for oceanographic ships in Alaska with these transportation linkages. Upgrading of the existing Seward station to a complete oceanographic facility will be initiated in November of 1974 and should provide an excellent operational center for Bering Sea research.

Communication network

The U. S. program for oceanographic research in the Bering Sea will need a communication network between ships and aircraft at sea and the operation centers at Fairbanks and Seward. This can be accomplished by single sideband radio, by marine radio or in cooperation with the U. S. Coast Guard radio facilities Communications with investigators outside Alaska can best be accomplished through TELEX or other telephone-linked media.

Management

An effective management system would involve an advisory council to give verbal guidance, a management council to organize the program and direct the research, and a manager and staff to coordinate the operation, including logistics, standardization, data handling and information exchange. The management council should have an executive committee who directs the activities of the manager; one member of the executive committee should be responsible for developing the international aspect of cooperation and coordination. As international programs develop, they should be closely coordinated and integrated with the activities of the U. S. program by the management council.

General

The logistics requirements for work in the Bering Sea are more extensive than for most other ocean areas because of the remote location of the study area in an environment hostile for man, especially during the winter season. The seasonal ice cover of the Bering Sea shelf and its concomitant effects on ocean processes require that intensive effort be given to studies of this region during the winter months in order to understand how the system functions. This places the highest priority for logistic support on those types of vehicles that will permit winter work in ice covered seas as well as in the adjacent open sea regimes. To meet this requirement, it is essential that a vessel capable of supporting oceanographic research in all seasons of the year be acquired and committed to operations in this area.

Management of all oceanographic research, on-going and planned for the future in the Bering Sea, should come under an international

Bering Sea research council. Each nation working in these waters should have a similarly structured research council to direct and coordinate the activities of workers within its own political structure. All data collected should be obtained by standardized methods established by intercalibration schemes and should be processed in a manner compatible to utilization by all nations.

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