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Bruun memorial lectures, 1991

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Modelling and Prediction in Marine Science

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Preface

Presented during the Sixteenth Session of the Assembly of the Intergovernmental Oceanographic Commission, this series of lectures is dedicated to the memory of the noted Danish oceanographer and first chairman of the commission, Dr. Anton Frederick Bruun. The "Bruun Memorial Lectures" were established in accordance with IOC Resolution VI-19 in which the Commission proposed that important intersessional developments be summarized by speakers in the fields of solid earth studies; physical and chemical oceanography and meteorology, and marine biology. the Commission further requested UNESCO to arrange for the publication of the lectures and it was subsequently decided to include them in the "IOC Technical Series".

Anton Bruun was born on 14 December 1901, the first son of a farmer; however, a severe attack of polio in his childhood led him tom follow an academic, rather than an agrarian career.

In 1926 Bruun received a PhD in zoology, having several years earlier already started working for the Danish Fishery Research Institute. this association took him on cruises in the North Atlantic where he learned from such distinguished scientists as Johannes Schmidt, C.G. Johannes Petersen and Th. Mortensen.

Of even more importance to his later activities was his participation in the Dana Expedition's circumnavigation of the world in 1928-1930, during which time he acquired further knowledge of animal life of the sea, general oceanography and techniques in oceanic research.

In the following years Bruun devoted most of his time to studies of animals from the rich Dana collections and to the publication of his treatise on the flying fishes in the Atlantic. In 1938 he was named curator of the Zoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945 to 1946 he was the leader of the Atlantide Expedition to the shelf areas of West Africa. This was followed by his eminent leadership of the Galathea Expedition in 1950-9152, which concentrated on the benthic fauna below 3,000m and undertook the first exploration of the deep-sea trenches, revealing a special fauna to which he gave the name "hadal".

The last decade of Bruun's life was devoted to international oceanography. He was actively involved in the establishment of bodies such as the Scientific committee on Oceanic Research (SCOR), the International Advisory Committee on Marine Sciences (IACOMS), the International Association for Biological Oceanography (IABO) and the Intergovernmental Oceanographic Commission (IOC); he was elected first Chairman of the Commission in 1961.

His untimely death a few months later, on 13 December 1961, put an end to many hopes and aspirations, but Anton Bruun will be remembered for his inspiring influencer on fellow oceanographers and his scientific contribution to the knowledge of the sea which he loved so much.

Contents

Opening Statement

Prof. Manuel M. Murillo,
First Vice-Chairman IOC

Chairman, Distinguished Delegates

In accordance with the wishes of the Assembly, at its Fifteenth Session, we have proceeded with the organization of three presentations, to be undertaken by distinguished scientists in the area of oceanography, and for this Session of the Anton Bruun Lectures, we will be accompanied by Professors Christopher Mooers, Egil Sakshaug and Chao Jiping and Wu Huiding.

The first of these lectures will be given by Dr. Christopher Mooers, from the United States of America. Dr. Mooers obtained his PhD from Oregon State University and is a visiting professor in the Marine, Earth and Atmospheric Sciences Department of the North Carolina State University. Dr. Mooers' academic experience includes participation in the scientific programmes of several universities in the United States and in Europe; among these, Miami, Delaware, New Hampshire and Liverpool University. Dr. Mooers has published more than sixty-five articles, within the domain of his specialty, physical oceanography, in particularly on the models of the ocean's circulation and the relation between the ocean and the atmosphere.

For this morning's lecture, Dr. Mooers will present a synthesis of the most important aspects of his research and the groups with which he works, in particular the programme COPS, Coastal Ocean Prediction System, whose goal is to produce a first generation prediction system for the marginal zones of the oceans and the coast. I give the floor to Dr. Mooers.

1. Overview of the Coastal Ocean Prediction Systems (COPS) Program

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Summary

The Coastal Ocean Prediction Systems Program, COPS, has been proposed in the USA to conduct the focused research and development necessary to produce, within a decade, the first-generation operational prediction system for the coastal ocean. (Here, the term 'coastal ocean' means the EEZ, estuaries, and great lakes, and the term 'prediction' is used in the broad sense of simulation, hindcast, nowcast, and forecast.) COPS is based upon societal need and scientific and technological opportunities. The societal need is to manage the coastal ocean ever more comprehensively as it becomes more impacted by climate and global change, local and regional pollution, and humankind's intensifying multiple uses. The societal thrust to manage the coastal ocean must be supported with improved understanding, monitoring, and modeling. The scientific and technological opportunities are those provided by improved coastal ocean process understanding; electronic sensors; acoustic, optical, radar, and satellite remote sensing; autonomous in situ observing systems; numerical circulation models; data-assimilation methods; tele-communications; workstations; supercomputers; database management systems; and computer animation. The operational manifestation of COPS is envisioned to provide a capability for simulating, reconstructing, tracking, and anticipating the synoptic evolution of coastal ocean circulation, stratification, and so forth, analogous to what the national weather services of the world provide for atmospheric weather patterns. It is also envisioned that this capability will be extended, in due course, to ecological, biogeochemical, and sediment transport processes.

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Introduction

The goal of this paper is to provide an overview of the Coastal Ocean Prediction Systems (COPS) Program, which was initially proposed in the USA in 1990. The COPS concept has evolved over three years of informal planning and a large, multi-agency, multidisciplinary workshop (Mooers, 1990) held in New Orleans in the autumn of 1989. COPS is a R&D (research and development) program focused on developing a first-generation predictive system for operational use within a decade. In this context, 'coastal ocean' includes the EEZ, estuaries, and great lakes, and 'prediction systems' includes simulation, hindcast, nowcast, and forecast systems. Regional numerical circulation models and real-time *in situ* and remote sensing systems are central to COPS. The first priority must be to develop predictive systems for the physical aspects of regional domains in the coastal ocean; the intent, however, is to add components for the chemical, biological, and sediment transport aspects of the system as soon as practicable, but, at the very least, there would be coordination with these other aspects from the beginning of the focused R&D.

COPS has been proposed in an era when there is an enormous growth in awareness of the value, both economic and esthetic, of the coastal ocean, and of the threats it faces from climate and global change as well as from local and regional pollution and other forms of misuse and excessive use. It is an era when record numbers of lives and financial resources are at stake in coastal boating and shipping, search-and-rescue missions, commercial and recreational fishing, oil and gas recovery operations, sand and gravel mining, tsunami and storm surge predictions, beach erosion protective measures, etc. It is also a time when a substantial coastal ocean science and engineering community and significant coastal ocean knowledge have been built up over the past quarter of a century; when numerical ocean circulation models are progressing apace with the ongoing advance of ocean process knowledge and supercomputers; when remote sensing, autonomous ocean sensors, and telemetry have become realities; and when computer graphics, database management, and telecommunications are revolutionizing the way scientific problems are approached. Thus, as governmental and other societal leaders grapple with the means to manage the coastal ocean, an operational coastal ocean prediction system would offer a scientifically and technologically advanced approach to acquiring much of the information needed to guide their decision-making. As a corollary, it would offer a model-assisted approach to monitoring and managing the coastal ocean.

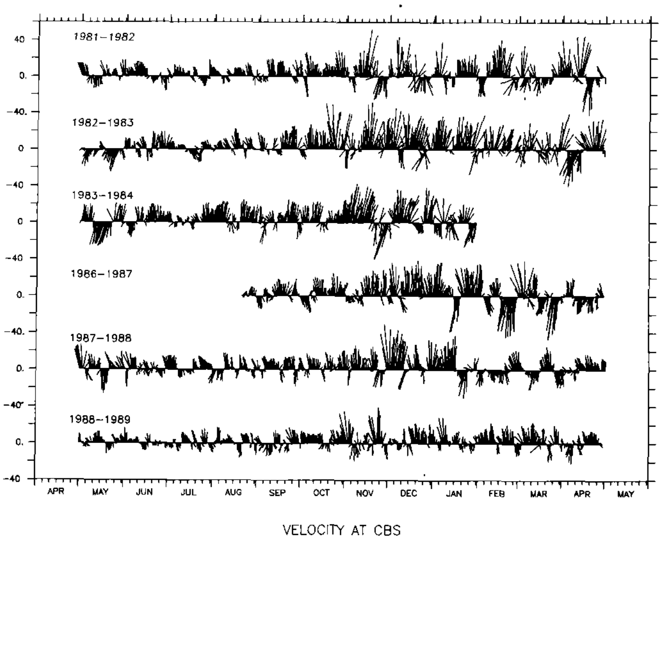
This paper reviews critical coastal ocean processes, R&D observing and modeling systems, and societal needs for coastal ocean prediction, and outlines a conceptual prediction system. Present operational capability and needed additional capability are reviewed, and an approach is proposed. Finally, possible partnerships for action are suggested, and national and international aspects are considered.

Coastal ocean processes

As the broad interface between continental and open ocean systems, the coastal ocean plays a major role in transport processes which are crucial to global ecosystems and biogeochemistry. It also has a physical, biogeochemical, and ecological dynamical life of its own, one which is rich in variability and biological productivity. The physical system is emphasized here because it has direct societal impact on its own, because its characteristics are crucial to the biogeochemical and ecosystems aspects, and because ocean science is presently better prepared to deal with it. In designing coastal ocean prediction systems, there are numerous natural processes and factors which must be considered. Below, several of the pertinent physical processes and factors are summarized, and then a few of the aphysical processes are enumerated.

The circulation, sea level, stratification, and water mass factors are the physical aspects of the coastal ocean of interest here because they control the advection and turbulent mixing of properties and materials. The transient circulation of the coastal ocean, as illustrated (Fig. 1) by the longest current time series (six years) in the coastal ocean (off Oregon) (Smith, 1991), is generally much stronger than the mean circulation, and it is energetic at time and space scales shorter than those characteristic of the open ocean circulation. It is driven by tidal forcing, sea and swell, atmospheric weather systems, seasonal cycles and interannual variability in winds and heating, river runoff, and open ocean eddies and meandering jets impinging upon it. Density structure can vary from highly stratified to fully mixed over a seasonal cycle, or even a weather cycle. In the mid-

Figure 1.
Long time-series of currents on the Oregon Shelf.



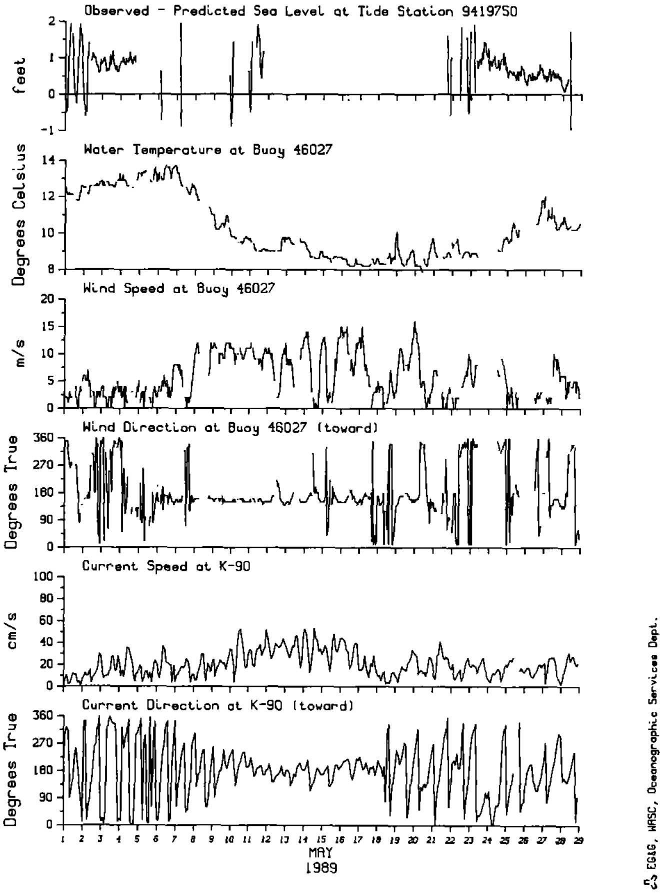
latitudes of eastern boundary regions, coastal upwelling is usually a dominant process, both physically and biologically, but such regimes breakdown into complex mesoscale variability. Analogously, in the mid-latitudes of western boundary regions meandering western boundary current jets influence the mesoscale variability of the coastal ocean. In high latitudes, freezing and melting processes, of course, are important for the development and evolution of ice-covered shelves. In low latitudes, evaporation or precipitation may be sufficiently great to be of major importance. Oceanic fronts of many scales and types are prevalent in the coastal ocean, especially in association with coastal upwelling, tidal mixing versus solar heating, tidal headlands, runoff plumes, juxtaposition of shelf and oceanic water masses, and impinging boundary currents. Mesoscale air-sea interaction, such as due to sea breeze and mistral wind regimes, plays a role, too. Surface mixed layers are largely controlled by winds and heating and cooling, while bottom mixed layers are largely controlled by tidal currents, gravity wave motions, and bottom roughness elements. On the inner shelf, surface and bottom mixed layers merge. Wind waves and internal waves add to the mixing environment and transport processes. Coastal physical processes are strongly affected by interaction with variable bottom topography, including the continental margin per se, submarine banks and basins, submarine canyons and capes, embayments, islands, and irregular coastlines. Similarly, the coastal atmosphere interacts with coastal orography and coastal ocean surface thermal structure to produce complexity in the atmospheric forcing of the coastal ocean. Coastal topography serves as a waveguide, making remote forcing a concern for observational, modeling, and analysis strategies, and leads to alongshore propagation of responses to wind events and a high degree of spatial coherence for some components of the pressure and alongshore velocity. Conversely, the short scales of alongshore variability in wind forcing and topography lead to a low degree of alongshore coherence in some components of the cross-shore velocity. Major changes in the coastal ocean environment can be anticipated if sea level rises in response to global warming. In addition to the obvious effects of coastal inundation and beach erosion, a global warming and sea level rise may be accompanied by an increased frequency and intensity of storms, and thus high winds and storm surge, and by altered oceanic general circulation, water mass formation, and river runoff, and thus altered water masses, stratification, and circulation in the coastal ocean.

These physical processes, and the highly variable consequent circulation and stratification, are responsible, through their roles in advecting and mixing nutrients into the sunlit upper levels, for the high primary productivity, and the resultant abundance of the higher trophic levels, found in the coastal ocean. For similar reasons, they are also critical determinants in eutrophication, hypoxia and anoxia events, algal blooms, the transport of fish eggs and larvae, and, thus, fisheries recruitment and management. Because of the richness of coastal ecosystems, the biogeochemical processes in the coastal ocean may play an important role in climate and global change through outgassing to the atmosphere, burial of organic carbon in the sediments, and so forth, all of which involve physical influences. The transient circulation and surface gravity waves are responsible for the erosion of beaches, resuspension of sediments, creation and destruction of bedforms, and the transport of sediments. The designers of coastal ocean predictions systems will need to identify the ocean processes to be addressed, then ascertain the space and time scales which characterize these processes, and, finally, strike a balance between the processes to be resolved and the requisite observational and computational resources.

Coastal ocean R&D observing and modeling systems

In recent years, a significant number of substantial coastal ocean R&D observing and modeling systems have been developed and utilized in different regions and in different process studies. For example (in the U.S.), in the observing system arena, under MMS sponsorship, EG&G Washington Analytical Services Inc., Scripps Institution of Oceanography, and other university and commercial groups recently operated a current meter array, with real-time telemetry and supporting drifters, satellite IR imagery, and shipboard observations for a few years off Northern California (Ryther et al., 1988). They produced real-time data reports (Fig. 2) which allowed them to perform quality control, timely maintenance, adaptive studies, and long-integration-time interpretations. They also produced experimental map products (Fig. 3) of surface winds and currents twice weekly for distribution to fishermen and others, as well as to project personnel. SeaSpace analyzed satellite IR imagery and superimposed surface wind and current vectors (Fig. 4) to reveal time sequences in patterns of mesoscale variability, especially alongshore convergences and compensatory offshore squirts and jets (Magnell et al., 1990). As another example, the University of New Hampshire (Irish, 1991), under NSF and EPA sponsorship, has operated telemetering moored conductivity and temperature chains (Fig. 5) in the Gulf of Maine intermittently for a few years. Most recently, an acoustic Doppler current profiler (ADCP) has been added to the sensor suite. The temporal evolution (Fig. 6) of the temperature, salinity, and density anomaly profiles over most of the water column (sensor depths of 4, 15, 25, 40, and 60 m in 64 m water depth) and over the summer season has been fully documented, which facilitates the monitoring of events. When the mid-August segment is expanded (Fig. 7), the large amplitude semidiurnal internal tides are evident. Velocity profiles (not shown) from the ADCP on the mooring documented the baroclinic nature of the flow in summer and its barotropic nature in winter. These moored time-depth

Figure 2.
Real-time data report from mooring off northern California.



Figuire 3.
Experimental map products for nearsurface winds and currents off northern California.

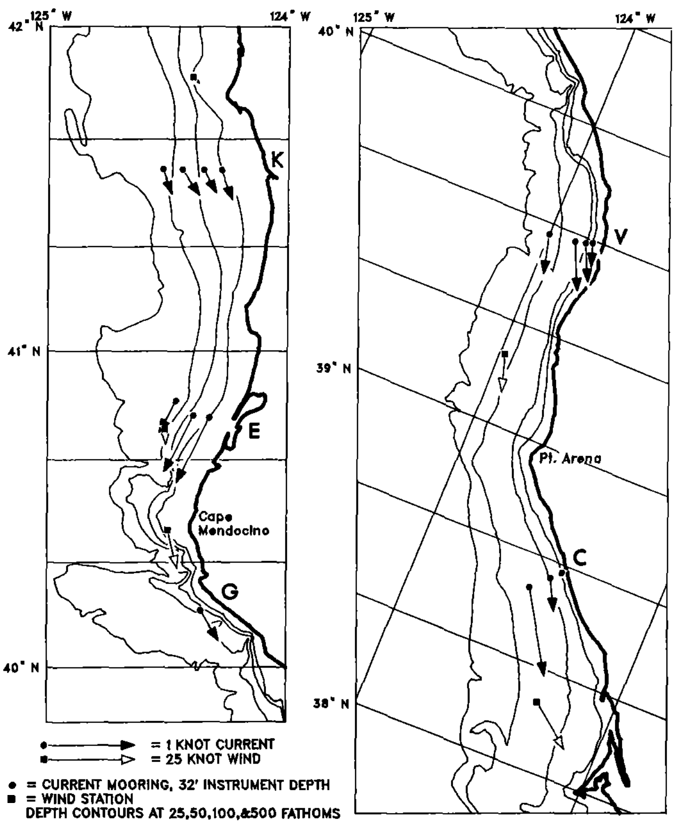
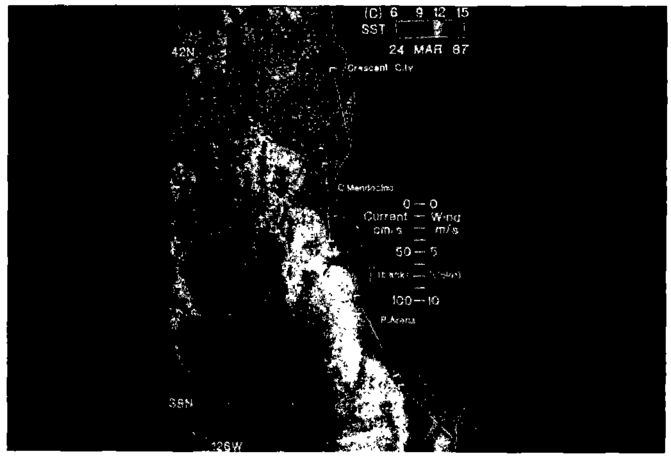
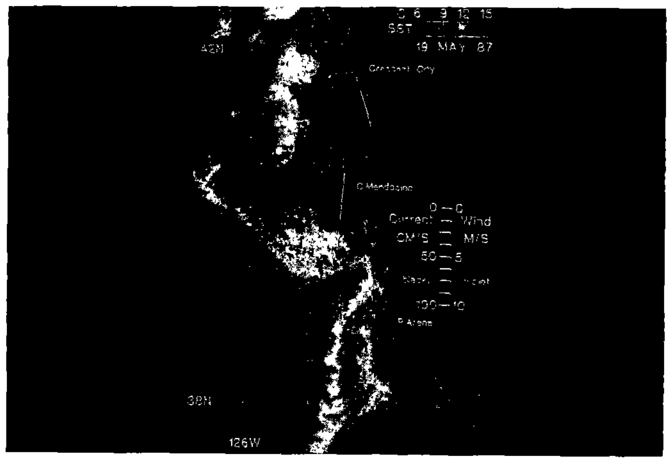


Figure 4.
Satellite IR images with superimposed wind and current vectors off northern California:

(a) 24 March 1987;



(b) 19 May 1987;



(c) 1 Aug. 1987.

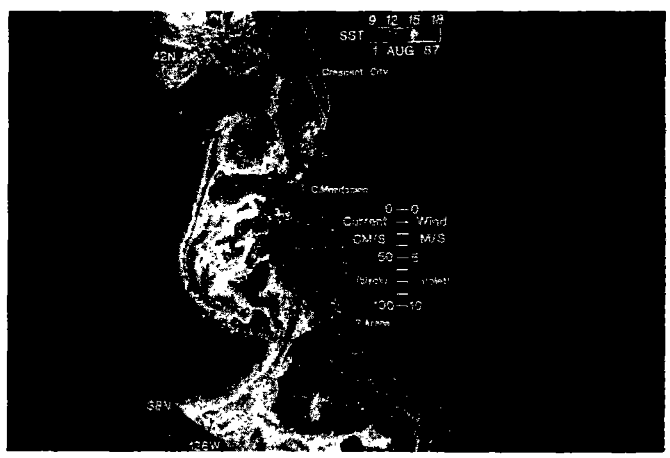


Figure 5.
Telemetering buoy system with a conductivity and temperature chain and an acoustic Doppler current profiler used in the Gulf of Maine.

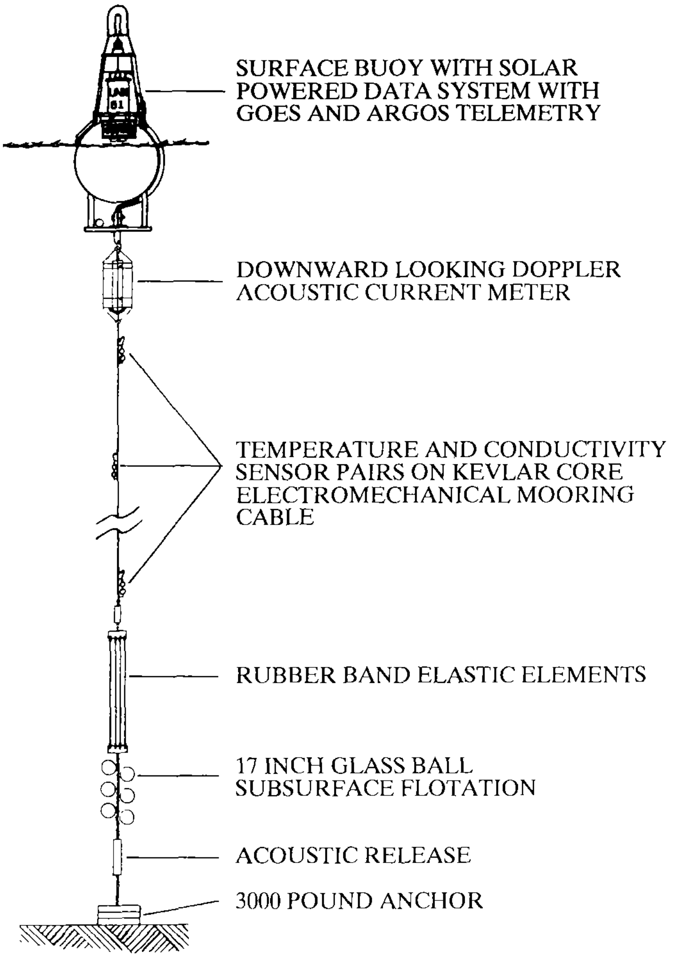
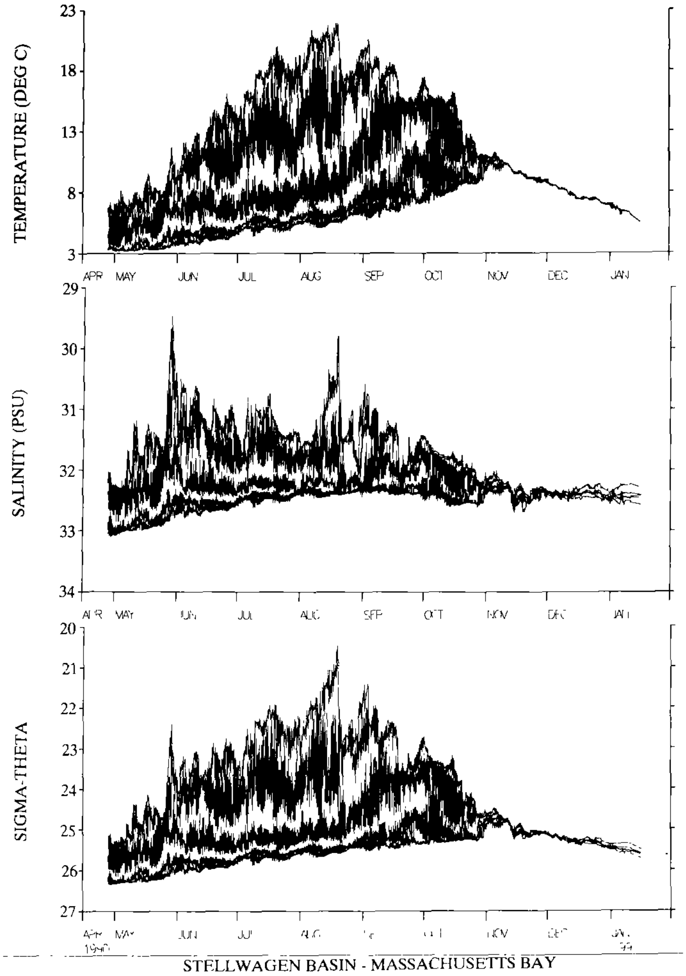


Figure 6.
Real-time-series from Stellwagen Basin in the Gulf of Maine through a seasonal cycle (sensor depths – 4, 15, 25, 45, 60 m; water depth – 64 m): upper panel - temperature; middle panel - salinity; lower panel - sigma-theta.



series are part of a larger study, which includes satellite-tracked drifters (Fig. 8) used to reveal the Lagrangian flow in real time (Geyer, 1991). As a final example, under DOE sponsorship, the Brookhaven National Laboratory (Falkowski et al., 1991) has developed a "biological current meter" array (Fig. 9), which uses a fluorometer for chlorophyll A estimates and an ADCP to provide acoustic backscatter data for zooplankton biomass and horizontal velocity estimates.

Similarly, in the modeling arena, over the past fifteen years or so, Prof. George Mellor (at Princeton University and GFDL) has developed, under sponsorship from NOAA, MMS, and INO, a primitive equation model with advanced physics, a free surface, and full bottom topography; it has usually been employed in regional studies as opposed to process studies. As such, it has been applied in numerous domains, including New York Harbor, where it validates well in comparison with tidal current analyses and salinity maps (not shown). As another example, it has been applied to a high resolution grid along the entire U.S. East Coast (Fig. 10). The model is initialized with high resolution temperature and salinity climatological means and topography. It is forced by climatological seasonal winds and heating, climatological seasonal cycle of Florida Current transport (30 Sverdrups), climatological mean Slope Water and Deep Western Undercurrent transport (40 Sverdrups) through the northeastern boundary, and mean Sverdrup interior transport (30 Sverdrups) through the southeastern open ocean boundary. A radiation boundary condition is applied in the region of the Gulf Stream outflow. After about five years of model time, the superimposed surface velocity and temperature fields for summer and winter (Fig. 11) illustrate the value of computer color graphics in displaying seasonal thermal structure, Gulf Stream jet meanders, eddy shedding, and the interaction of the Gulf Stream and shelf flows (Mellor and Ezer, 1991). In a parallel effort, over the past decade, Prof. Dale Haidvogel (now at Rutgers University and NCAR) has developed independently, under sponsorship from ONR, NSF, and INO, a primitive equation model over the past decade which differs in its architecture, numerics, and physical completeness; it has usually been used in process studies rather than regional studies. As applied to

Figure 7.
Expanded scale for the mid-August segment in Figure 11.

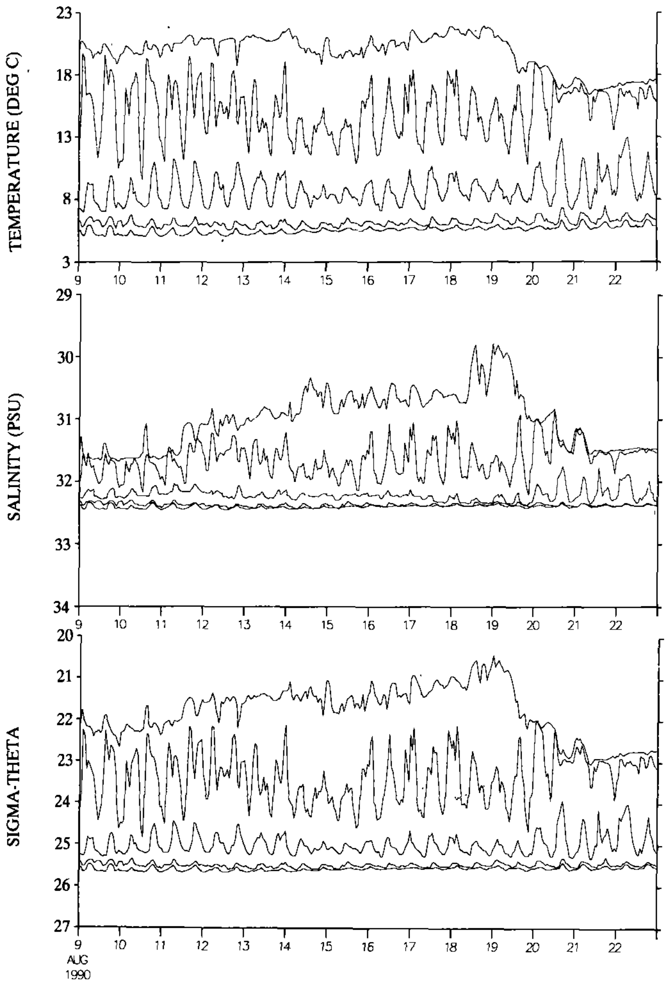
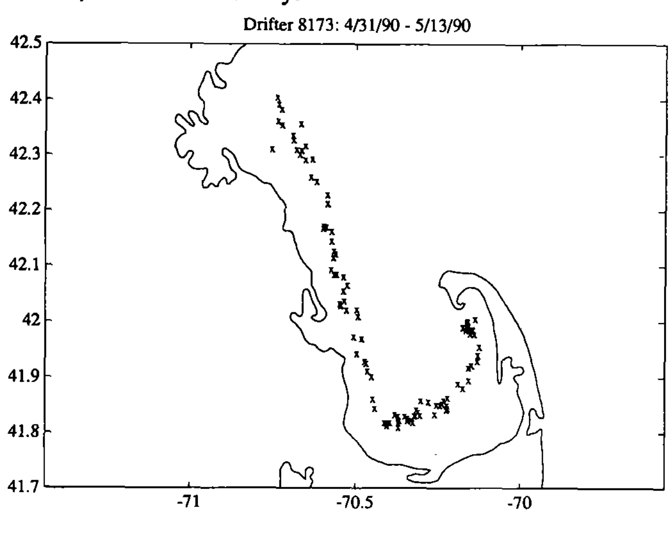


Figure 8.
Satellite-tracked drifter in the Gulf of Maine/Massachusetts Bay.



the Northern California coastal upwelling and jet system and its irregular coastline, an initially stable jet becomes unstable after a few months and begins to form cross-shore filaments, jets, and mesoscale eddies (Haidvogel et al., 1991). Cross-shore transects (not shown) through the filament reveal the subsurface structure of the velocity field, including strong downwelling associated with the emerging system. A time sequence (Fig. 12) of horizontal maps of density and vertical velocity depict the rapid evolution of the jet and eddy system over the period of a month. As an auxillary calculation, the fully 3-D Lagrangian trajectories (not shown) of water parcels reveal strong downwelling, and presumably that of any passive tracers (e.g., nutrients, fish eggs, phytoplankton, toxic contaminants, etc.) during the evolution of the jet and eddy-shedding process (Hofmann et al., 1991).

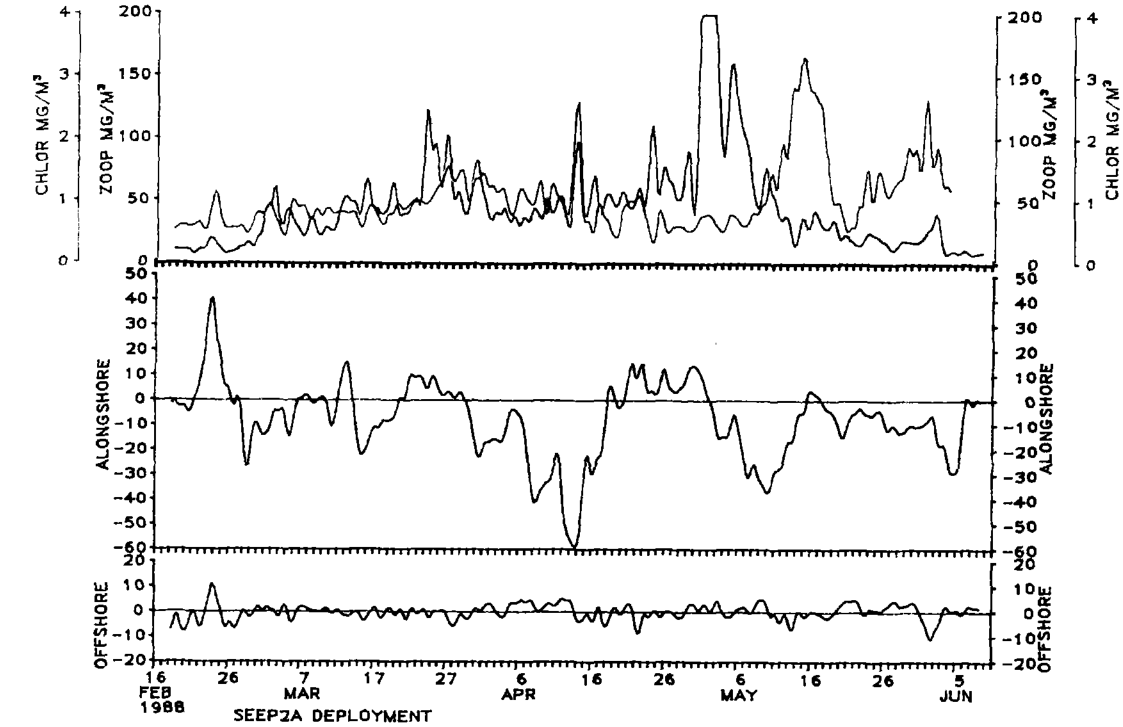
Other examples of emergent observing and modeling system capabilities relevant to COPS could be offered. Overall, it is noteworthy that these capabilities are products of studies sponsored by a variety of agencies and involve a variety of institutions and investigators. There is no national coordination, perhaps beneficially. One consequence, however, is that none of these efforts is sustained for more than a few years nor oriented toward achievement of focused, long-term goals and objectives for coastal ocean prediction systems. The results described above indicate that there are scientific opportunities and technological possibilities to begin to move in that direction with a sustained campaign of coastal ocean prediction studies, as in the proposed COPS Program.

Societal needs

An operational coastal ocean prediction system will consist of a validated, coastal ocean-atmosphere coupled, real-time observing/numerical modeling system which is able to assimilate all the available and relevant observations into the model in order to make best estimates of the fields of interest throughout the domain of concern. As such, it would serve as an information management system which can provide hindcasts, nowcasts, and forecasts of known quality, and also function in the simulation mode. These capabilities would facilitate much basic research associated with, for example, better understanding of coastal ecosystems, and applied research associated with, for example, improvement of oil spill trajectory and effects forecasting. They could also serve many societal needs directly.

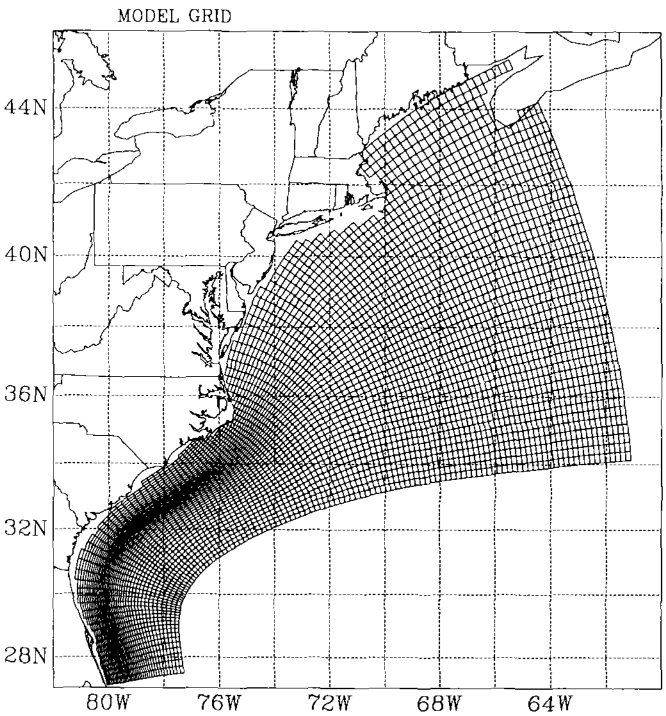
The societal needs for operational coastal ocean prediction systems can be categorized as follows: planning, operations, and assessment for the coastal ocean. The planning category includes simulations of the physical and ecological response of the coastal ocean to plausible climate and global change scenarios, proposed physical structures and waste discharges, and other societal activity. The operations category includes real-

Figure 9.
Depth-integrated, moored time-series (water depth: 90 m; location: mid-Atlantic Bight): Chlorophyll a concentration (from three flurometers); Zooplankton biomass (from acoustic backscatter intensity-; Alongshore velocity (from acoustic Doppler current profiler); Offshore velocity (from acoustic Doppler current profiler).



Integrated chlorophyll a concentration and zooplankton biomass from the shelf/slope frontal region of the mid-Atlantic bight at 37 42'N , 74 20'W in 90 meters of water. Chlorophyll a data were obtained from 3 moored fluorometers at depths of 19, 41, and 87 meters by C.D. Wirick, BNL. Zooplankton biomass was derived from the amplitude of the acoustic backscatter from a bottom mounted 307 KHz RDI acoustic Doppler current profiler by C.N. Flagg, BNL. Velocity data (cm/sec) from the ADCP were also vertically averaged after low-pass filtering.

Figure 10.
Orthogonal curvilinear grid for the Mellor/Princeton East Coast Circulation Model.

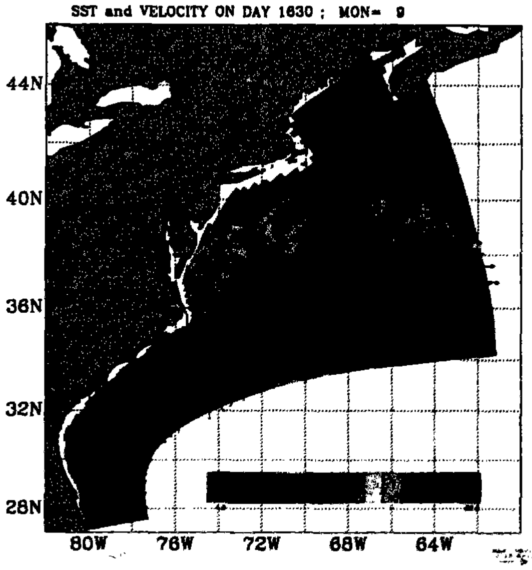


time support to: ongoing boating, shipping, and fishing; dredging and disposal; sewage outfall operation; and oil spill and other pollutant clean-up activities. The assessment category includes reconstruction of environmental event scenarios, potential impact studies and risk analyses, estimation of the present and future states of the coastal ocean environment, and evaluation of candidate and actual monitoring systems.

Hence, within the foreseeable future, a coastal ocean prediction system is seen as playing a central role in coastal environmental decision-making. It will offer environmental managers the opportunity to take advantage of modern ocean sensing, ocean modeling, and computing and communications technologies, and, above all, the contemporary scientific understanding which enters into the design, testing, and operation of observing and modeling systems.

Figure 11.
SST and Surface Velocity form the Mellor:Princeton East Coast Circulation Model:

(a) Day 1630 (summer);



(b) Day 1780 (winter).

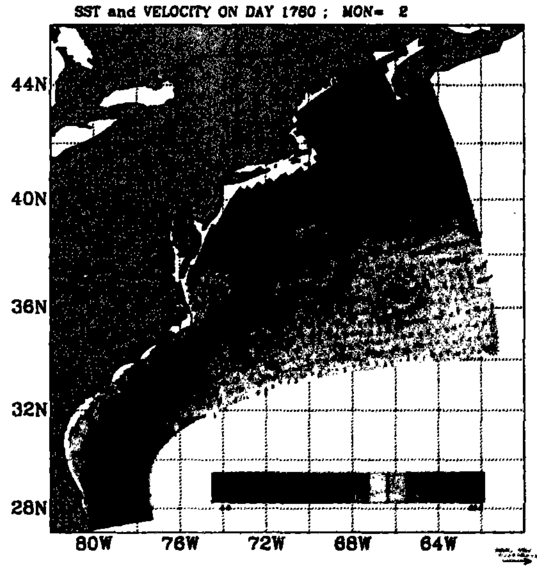
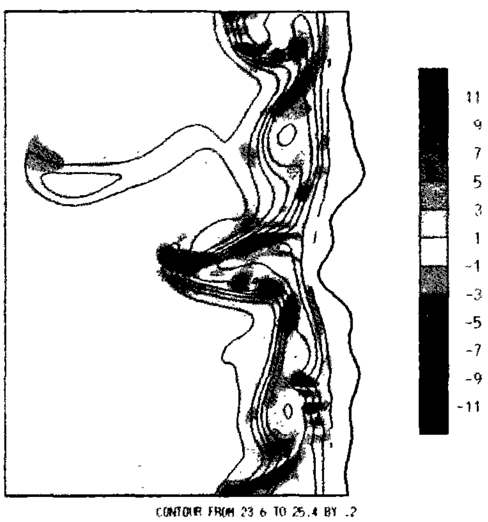
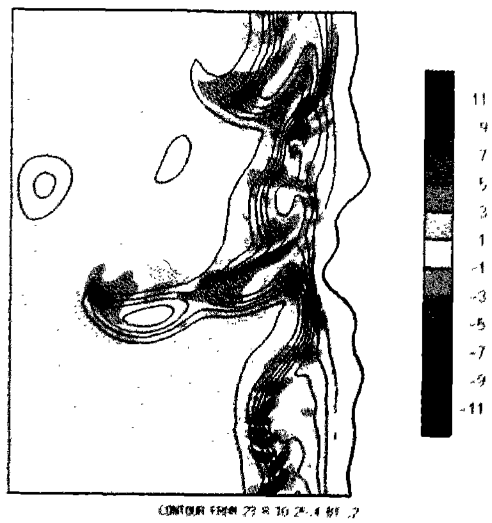


Figure 12.
Horizontal maps of density (black contours) and vertical velocity (colored zones) at 100 m depth from the Haidvogel/SPEM model:

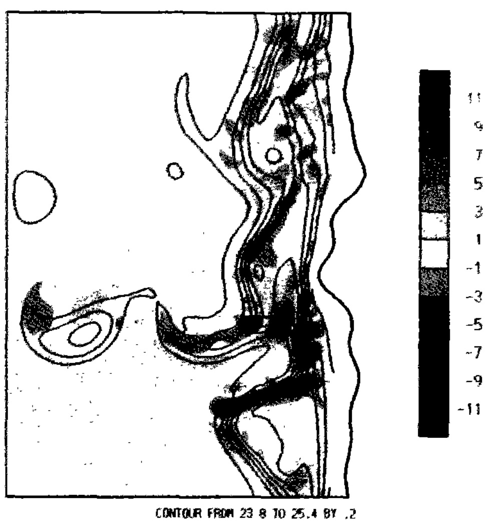
(a) Day 140



(b) Day 156



(c) Day 172



Needed system attributes

This is an opportune juncture at which to contemplate the functional attributes of a coastal ocean prediction system designed to help model, monitor, and manage the coastal ocean. (Many ideas useful to this purpose were developed during Ocean Prediction Workshop 1986 (Mooers et al., 1986) as well as the COPS Planning Workshop (Mooers, 1990).) First, the system must be continually operating, and it must address the time-varying circulation and density stratification over the variable topography of a regional domain, possibly on only a relatively coarse grid. Second, it must be a reliable and validated system, with documented error characteristics and statistics. Third, it must be possible to augment the system with high-resolution, portable, rapidly-deployable capability during local and regional events to support special societal demands--e.g., storm surge forecasts, search-and-rescue operations, oil spill trajectory hindcasts and forecasts, toxic algal bloom alerts, fishing campaigns, or impact studies for oil and gas drilling and aquaculture installations. Fourth, it must be possible to extend the system to incorporate biogeochemical, ecosystem, and sediment transport processes and dynamics.

Fifth, the system should be compatible with coastal atmospheric and hydrological prediction systems and wetlands and watershed ecological information management systems, so that it can be a component in a total coastal (including oceanic, atmospheric, and terrestrial components) information management and prediction system. It would also be designed to be the coastal ocean component of the proposed global ocean observing system.

Sixth, the system must meet the needs of: scientific researchers concerned with long-term studies of coastal ecosystems; industrial, commercial, and governmental managers concerned with coastal ocean operations; and environmental managers and environmentalists concerned with the assessment of the state of the coastal ocean and its response to natural and anthropogenic variability and change. In particular, all parties would want to use the coastal ocean prediction system to detect, with known statistical reliability, and understand anthropogenically-induced change in the presence of natural variability. These considerations imply that the system must eventually produce high-level information which synthesizes large volumes of raw data into readily understandable products--e.g., interactive color videos displaying, for example, the response of the coastal ocean environment and ecosystem to the passage of a hurricane.

Components of a desired system

Though the specific components of a desired, or even an initial, operational coastal ocean prediction system cannot be prescribed in full detail today, because, in fact, they are topics of applied research yet to be performed, some of the components can be recognized, at least in broad outline, from current operations or basic research. For example, the observing system will inevitably include coastal tide gauges, weather stations, and river runoff gauges. It will also include moored buoys with current profilers, conductivity and temperature chains, bottom pressure sensors, and meteorological surface buoys. These elements will be deployed in a permanent, coarse regional array, and they will all telemeter their data in real time. This basic system will be supplemented by the full range of remote sensing data (IR, visible, microwave, radar, etc.) available from satellites, periodic aircraft overflights, and coastal sites. It may well be augmented by the systematic deployment of surface drifters and subsurface floats, either or both of which may be instrumented. Even in its early stages, the sensor suite of the moored array would probably also include fluorometers, dissolved oxygen sensors, and optical sensors; additional acoustical, biological, and chemical sensors would be incorporated as they are developed and proven.

The modeling system will consist of numerical models with comprehensive nonlinear dynamics, advanced numerical methods, data-assimilation capability, a database management system, and computer graphics. For a typical coarse-resolution regional model, the spatial resolution will be a few kilometers in the horizontal and 10 to 20 levels or modes in the vertical. For a typical fine-resolution, limited-area model, the resolution may be ca. 100 m in the horizontal and ca.100 levels or modes in the vertical. These models will have a free surface in order to treat tides and storm surges; thus, the time resolution for the surface (barotropic) mode will be ca. 1 min. and that for the internal (baroclinc) modes will be ca. 1 hr. The barotropic and baroclinic modes will be coupled. The coastal ocean circulation models may be coupled with a mesoscale-resolution, regional atmospheric model, which in turn may be nested in a global atmospheric prediction system. Output from the physical model will be used to prescribe the advective and mixing elements of ecosystem, biogeochemical, and sediment transport models. The characteristics of the latter models will be determined by the scope and scales of the processes of interest and the availability of observations.

The modeling system and observing system will be closely linked; in fact, they should be developed together to the extent possible. Data from the observing system will be used to establish a climatology of mean conditions, and of variability about that mean, as part of the model development and evaluation process. A major purpose of the observing system will be to provide information for initializing the model, updating its dynamical boundary conditions, and updating interior values; it will also be used to verify the model as part of the quality control process. As a corollary, a database management system will be a significant component, not only for dealing with the archival and real-time data, but also for handling, displaying, and storing a selected subset of the high-level fields produced by the models.

The prediction system will generate a variety of products with estimated error fields. The physical prediction system, for example, will produce maps of horizontal and vertical velocity, temperature, and salinity on surfaces of interest; vertical transects of these variables; and their time-depth plots. There will be other, more specific products, such as maps or time series of mixed layer depths, thermocline strength, surface wave heights, and tide heights. As a byproduct, fields of surface, internal, and bottom mixing parameters will be calculated and made available to ecosystem, biogeochemical, and sediment transport models. In addition to these Eulerian presentations of information, there will be Lagrangian presentations, such as three-dimensional particle trajectories. Analogously, the ecosystem and biogeochemical models will produce maps, etc., of the concentration of nutrients, dissolved oxygen, plankton, and so forth; Lagrangian trajectories of particles will be available, too. All of this information must be accessible to environmental managers and research scientists through interactive computer color graphics animation. In many instances, environmental managers will want to have expert-system-type decision aids, which will automatically detect and alert them to the occurrence, or even probable development, of events as "witnessed" or "anticipated" by the coastal ocean prediction system.

Present operational capability

For purposes of the present discussion, the present U.S. operational capability will be taken as representative. The operational observing systems functioning in the U.S. coastal ocean consist of several dozen NOAA/NOS tide gauges, a few dozen NOAA/NWS meteorological buoys (Fig. 13) (Hamilton, 1991), and AVHRR imagery from two NOAA/NESDIS polar-orbiting satellites. The USGS provides several dozen stream gauges for river runoff. In some instances, repeat NOAA/NMFS fisheries surveys and some ship-of-opportunity XBT lines may contribute operational observations within the coastal ocean. NOAA/NOS has begun to deploy a system for real-time water level and current measurements, called PORTS (Hess, 1980), for support of operations in major harbors and estuaries.

The operational modeling systems functioning in the U.S. coastal ocean consist of a storm surge model run by NOAA/NWS and trajectory models run by NOAA/NOS, USCG, and MMS for oil spills and USCG for search-and-rescue. The Navy runs wave spectral, ocean thermal structure analysis, and ice models for broad ocean regions; however, there is no special focus on the coastal ocean. (The Navy intends to run ocean circulation models operationally.) NOAA provides SST analysis products from AVHRR images and blends of such images, ship reports, and buoy data (Fig. 14); it also provides primary wave direction and period maps.

Figure 13.
NOAA/NW's NDBC buoy locations.

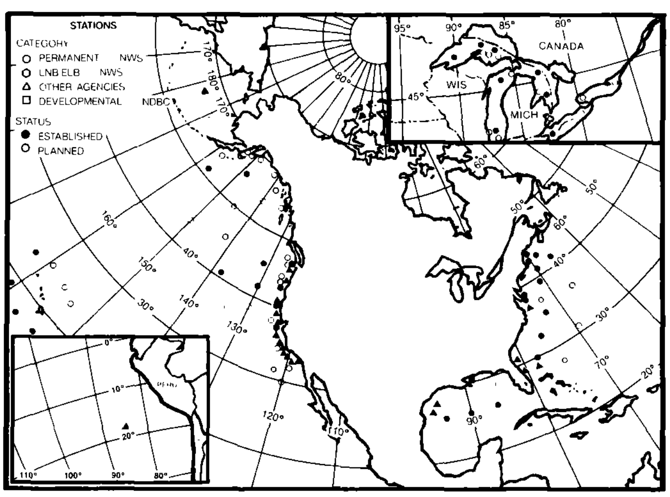
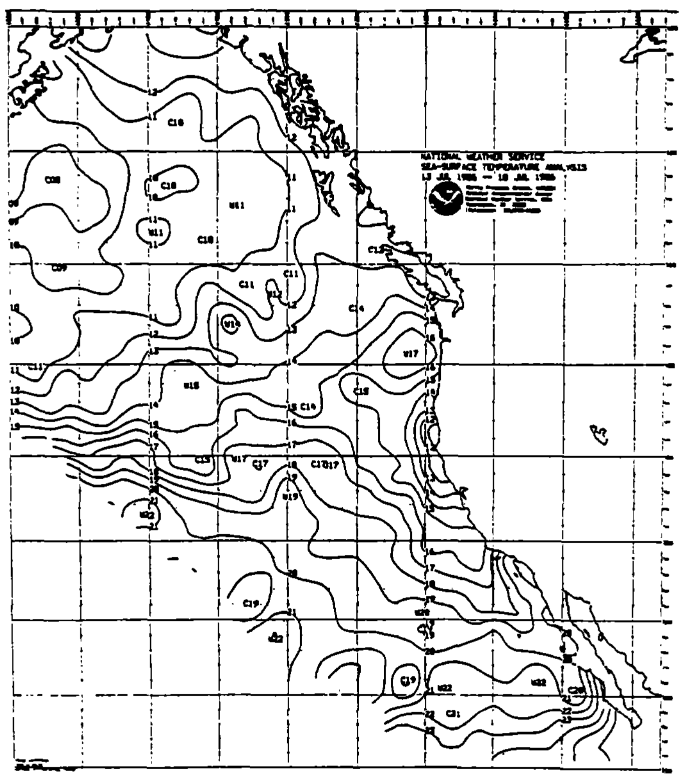


Figure 14.
NOAA/NW's Pacific Coast one-degree resolution satellite, ship, and buoy blended SST analysis based on five-day running mean.



In support of short-term, limited-area studies (as discussed in Section III), the basic research community and environmental companies have taken significant steps in developing, for the coastal ocean: real-time, moored and drifting observing systems; circulation models; and sophisticated process knowledge. However, the observing systems have not been made robust for long-term use, and the models have not been thoroughly validated, nor complemented with data-assimilation schemes. Hence, their transition to operational use has yet to be attempted, let alone achieved.

Needed additional capability

By comparing the present capability to what is desired, it is possible to discern some of the needed additional capability and effort. In the observing system arena, permanent moored buoy stations, with comprehensive suites of ocean sensors, need to be established. Conceivably, this could be achieved, in some instances, by augmenting existing meteorological buoys with ocean sensors, especially current measurements for long-term Eulerian statistics. The meteorological buoy network itself may need to be enhanced, especially for increased cross-shore resolution. All major field studies in the coastal ocean should be encouraged to adopt real-time elements. A regular program of Lagrangian buoy deployments should be commenced to develop long-term statistics of Lagrangian dispersion, among other things. A regular program of aircraft remote sensing flights should be undertaken. The adequacy of presently planned (NOAA, NASA, and other) satellite remote sensing systems should be reviewed from the perspective of coastal ocean information needs, and corrective action initiated as needed. Promising new technologies, e.g. coastal radar systems and acoustic backscatter systems, should be explored, too. Overall, the inadequacies of present operational observing systems are the greatest limiting factor to the development of coastal ocean prediction systems. Hence, a systematic and aggressive approach to developing, testing, and evaluating alternative coastal ocean observing systems is needed.

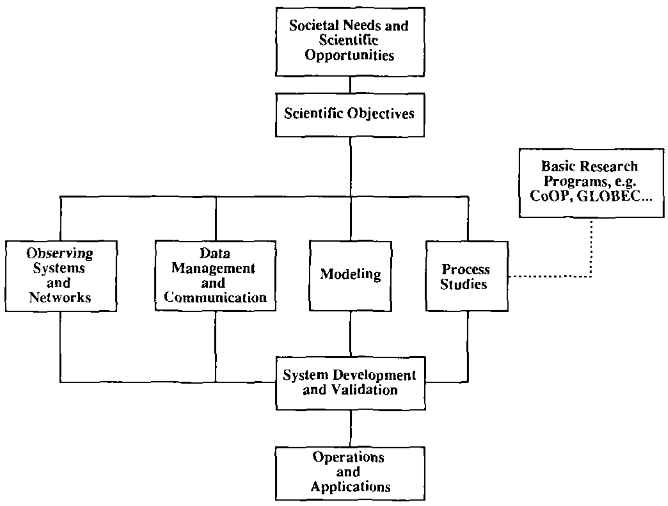
In the modeling system arena, based on the fine progress made to date with process models, more emphasis needs to be given to the development and evaluation of regional models. More basic research is needed on open boundary conditions. Coastal atmospheric models need improvements to deal with coastal air-sea-land interactions. There is a great paucity of activity in the evaluation of models relative to observations. Among other criteria, models should be evaluated for their Lagrangian dispersal properties. In many cases, adequate observations do not exist for these purposes, or the coastal ocean climatology has not been conveniently organized. Data-assimilation schemes appropriate to the coastal ocean are in serious need of development. Again, the lack of suitable observations is a serious limiting factor. Conversely, models can be used to help design the needed observing system networks through conducting Ocean Observing System Simulation Experiments (OOSSEs) for the coastal ocean.

To bring observing and modeling systems into congruence, joint observing system/modeling system studies are needed. This has seldom been done in the coastal ocean and never wholly satisfactorily. A significant investment in time, effort, and financial resources is required, plus a high degree of organization. To stimulate the requisite feedback between observations and models, and to cultivate feedback from potential user groups, it is highly desirable for such studies to include the development and provisional distribution of prototype products. To ensure a high degree of objectivity, disinterested third parties should be involved in the design, implementation, and peer-reviewed documentation of evaluations.

Proposed approach

To move from the present capability of coastal ocean observing systems and modeling systems used in research to an operational coastal ocean prediction system, several steps need to be taken in a fashion similar to the proposed COPS program (Fig. 15). First, an interested group of experts must be assembled to oversee an

Figure 15.
Major Program Elements (ala TOGA) for COPS.



experimental prediction and evaluation program. Second, alternative observing and modeling systems must be considered through a series of experiments and comparisons. The development of an objective consensus of the capabilities and limitations of the evolving observing and modeling systems is a high priority objective. It will be desirable to run one or more models in a quasi-operational mode with operational data, but possibly in a delayed, offline fashion. (Through experience with common data sets, there will be a tendency for the models to converge toward a common parameterization of subgridscale processes and other model design factors.) Third, this experimentation and evaluation effort will lead to observing and modeling system selection, which will make possible the difficult but essential transition from research to operations. (Some of the required work can be done in a research environment, but eventually prediction systems must be exercised in an operational computational environment, i.e., in either an actual or simulated operational center (ala ECMWF), so as to have access to operational data streams and to encounter the challenges of operational schedules.) Fourth, in parallel with the experimental and evaluatory efforts, provisional products should be developed and disseminated to help cultivate and define the "market" for prediction products. Fifth, system integration of the various components selected must be accomplished to create a working prototype which can be used as the basis for defining a first-generation, operational coastal ocean prediction system. (This approach could be adopted on a national scale by a few large countries, and it should be coordinated on the international scale for the benefit of all the world. One or more dedicated computational centers may be required; the operational and research meteorological communities can offer excellent examples and guidance in these matters.)

Infrastructural and hierarchical issues associated with an eventual operational coastal ocean prediction system need consideration, too. In due course, there will probably be an operational global ocean observing and modeling system which will provide boundary conditions for regional coastal ocean models, which in turn will provide boundary conditions for models of estuaries, sounds, embayments, etc. The needed connections may come through a linked system of global, multinational, national, and subnational R&D and operational centers.

Overall, a sustained experimental approach similar to TOGA--which links real-time observing systems with numerical models, researchers with operational entities, and research results with prototype product development--is needed for the coastal ocean. The same or a similar strategy needs to be pursued in several coastal ocean domains to ensure robustness of the system prior to wide-scale adoption. These considerations led the scientific leadership group of COPS to propose the following "goal and objectives statement" as a basis for program design:

COPS goal

To develop and validate a predictive system for the U.S. coastal ocean, including the capability to forecast conditions in the EEZ for several days and to simulate them for several years.

COPS objectives

1. To determine the extent to which the coastal oceans are predictable on time scales of hours-to-days and understand the processes that relate to this predictability.

2. To develop a set of efficient hindcast, nowcast, and forecast systems including observational networks, dynamical models, and data-assimilation techniques, suitable for continuous, large-scale regional use. These regional systems should be complemented by rapid-implementation, high-resolution systems to provide intensive, highly accurate, subregional forecasts in support of specific events.

3. To couple the physical predictive system to biological, chemical, and geological components in order to advance interdisciplinary ocean science, to facilitate the management and utilization of coastal marine resources, and to enable simulations of the coastal ocean response to various global change scenarios. The multidisciplinary version of the coastal ocean prediction system should be structured so that it is available for the solution of real-time environmental problems, the study of ecosystem processes, and the management of coastal resources and environmental quality.

Partnerships for action

The development of a coastal ocean prediction system will require several kinds of partnerships. For example, on a disciplinary basis, development of the physical portion of the system will require collaboration of coastal physical oceanographers, ocean engineers, hydrologists, and meteorologists. Of course, extension of the system to cover ecological, biogeochemical, and sediment transport processes will require partnerships with biological, chemical, and geological oceanographers. It would be wise to incorporate the participation of economists and environmental professionals, too.

On a functional basis, the system development will be most efficient if there are partnerships between the coastal ocean research, monitoring, operational services, and environmental management communities.

On an institutional basis, to marshall the talent and financial resources required for system development, and to exploit the attendant opportunities afforded by an operational system, a partnership between academia, industry, and government will be needed, especially if there is to be an environmental information industry for the coastal ocean in the next century.

National and international aspects

Coastal geography exerts appreciable control on the physical aspects of the coastal ocean, which in turn influence coastal ecosystems so that both the physical systems and ecosystems are organized regionally. This natural regional organization of the coastal ocean leads to semi-closed systems which are efficiently treated as a whole, but for which exchanges with adjacent coastal regions and the open ocean must be taken into account. For nations with lengthy coastlines, their coastal ocean may encompass more than one coastal ocean region. Conversely, some coastal ocean regions are bordered by more than one nation. In the first case, a nation must deal with more than one coastal ocean region, and it may be most efficient to have separate regional prediction systems. In the second case, several nations may wish to pool resources and efforts to create and operate a regional prediction system.

There are obviously enormous opportunities for information and technology transfers, training and education, and personnel exchanges associated with a world-wide effort in coastal ocean prediction system R&D and operations.

As a bare minimum, there will be a need for international coordination with the development and operation of the Global Ocean Observing System and other aspects of the "Climate and Global Change" program. The IOC, WMO, and UNEP would presumably be involved in any such coordination. On the other hand, there may be opportunities for IOC to play a very dynamic role in facilitating or actually leading the development of coastal ocean prediction systems.

Summary and conclusions

The major considerations for designing, developing, and operating a coastal ocean prediction system have been identified here in broad outline. The scientific and technological opportunities and the societal needs exist to design, develop, and operate such a system. Needed is a commitment to a sustained period of focused research in close collaboration with evolving operational services, in a fashion analogous to the manner in which the TOGA program has been conducted, so that a working prototype can be developed, demonstrated, evaluated, and modified.

It is opportune to proceed with COPS. Within a decade, a first-generation, operational coastal ocean prediction system could be functional, given a concerted, focused R&D effort and adequate resources.

IOC (and WMO) could play a major role in helping to bring an international group of experts together to develop a coordinated program of coastal ocean observing and modeling system intercomparisons. IOC might play an even larger role in actually organizing coastal ocean prediction system development and operation, including the fostering of multinational, regional operational centers.

Acknowledgements

Gratitude is expressed to colleagues who contributed material to this paper; in particular, Drs. Robert Bernstein, Paul Falkowski, Rocky Geyer, Dale Haidvogel, Glenn Hamilton, James Irish, Bruce Magnell, George Mellor, and Robert Smith. This paper reflects, in part, the findings of the COPS Planning Workshop, and the subsequent deliberations of the COPS Interim Scien-tific Planning Group: Drs. John Allen, Larry Atkinson, Kenneth Brink, Wendell Brown, Paul Falkowski, Thomas Lee, George Mellor, Christopher Mooers, Allan Robinson, Clinton Winant, Frank Eden, and Joseph Huang. Preparation of this paper has been an unspon-sored effort supported in part by the Institute for the Study of Earth, Oceans and Space, University of New Hampshire.

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GLOSSARY OF ACRONYMS

ADCP - Acoustic Doppler Current Profiler

COPS - Coastal Ocean Prediction Systems Program

DOE - Department of Energy

ECMWF - European Center for Medium Range Weather Forecasting

EEZ - Exclusive Economic Zone

EPA - Environmental Protection Agency

GFDL - Geophysical Fluid Dynamics Laboratory

INO - Institute for Naval Oceanography

IOC - Intergovernmental Oceanographic Commission

MMS - Minerals Management Service

NASA - National Space Aeronautics and Space Administration

NCAR - National Center for Atmospheric Research

NOAA - National Oceanic and Atmospheric Administration

NESDIS - National Environmental Data and Information Service

NMFS - National Marine Fisheries Service

NOS - National Ocean Service

NWS - National Weather Service

NSF - National Science Foundation

ONR - Office of Naval Research

R&D - Research and Development

TOGA - Tropical Ocean and Global Atmosphere Program

USACOE - United States Army Corps of Engineers

USCG - United States Coast Guard

USGS - United States Geological Survey

WMO - World Meteorological Organization

XBT - Expendable Bathythermograph

Prof. Manuel M. Murillo

In respect to our Anton Bruun Lectures, the next speaker is Dr. Egil Sakshaug from Norway. Dr. Sakshaug obtained his PhD in Marine Botany from Oslo University. He is Professor at Trondheim University and Associate Professor at its Biological Station. He has also been a visiting scientist at Rhode Island University, the Bigelow Laboratory and Scripps Institution of Oceanography.

The field of Dr. Sakshaug's research is marine phytoplankton ecology, first of all with emphasis on nutrient limitation and more recently on the effects of the light intensity on the growth of phytoplankton. In recent years, his work has focussed on climate and the oceans, in particular methods for studying the biological carbon pump origin.

The results of Dr.Sakshaug's work are to be found in more that forty publications and several documents related to the prospects or perspectives for the development of oceanographic research in Norway. It was his responsibility to write the research plan for his country's programme concerning marine ecology in the Arctic, the programme Pro Mare. Pro Mare arranged sixteen cruises to the Barents Sea, the mission of which was to study the pelagic ecosystems. The lecture that Dr. Sakshaug will give us this afternoon includes some of the important results of this Pro Mare programme research, especially that which highlights how physical factors and primary production are intimately coupled. I invite our speaker to begin his presentation. Thank you.

2. The Barents Sea: The Physical-biological Connection

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Summary

The Barents Sea is a shelf sea of average depth 230 m and area of 1,4 million km^2 north of 76°N; it is characterized by low-salinity arctic surface waters; waters of the southern half are Atlantic. The southwestern part is permanently ice-free, while the remaining part is seasonally covered by ice; multiyear ice is scarce. The Barents Sea is known for its large stocks of commercially important fish (capelin, cod), seals and seabirds. Yet winter concentrations of plant nutrients which support the Barents Sea ecosystem are only 1/2 and 1/3 of those in the Bering Sea and the Antarctic Ocean, respectively; i.e. the same as in the Northeast Atlantic in general.

Being a polar sea exposed to large annual fluctuations in ice cover, climate and temperature of inflowing atlantic water, the Barents Sea is characterized rather by dramatic fluctuations in standing stocks of commercially important species than by "ecological" balance. This has been particularly true for the capelin, seal and bird stocks in the last five years.

The northern half of the Barent Sea is characterized by a spring bloom which takes place at the ice edge as soon as the ice starts to melt. This bloom follows the retreating ice edge and occurs, in principle, later the far north. Because of a marked pycnocline which persists until late autumn, the remaining part of the growth season is characterized by oligotrophy. Thus zooplankton are given one big but short-lasting meal per year, and annual primary production is low, maximum 50 g C m^{-2} y^{-2}. In the southern half the pycnocline can be deeper, thus causing a more durable bloom. The depth of mixing in the southern part of the Barents Sea is highly influenced by weather patterns; thus "new" nutrients are more or less regularly supplied after the spring bloom. Mathematical models indicate an annual production of 80-100 g C m^{-2} y-1. Primary production is thus strongly coupled to weather patterns. Presumably wind-forced deep mixing alternating with calm weather such as caused by regular passage of atmospheric low pressures optimize conditions for phytoplankton production.

Introduction

The Barents Sea covers about 1.4 million km^2, of which about half is seasonally covered by ice. Multiyear ice is in the main absent. The Barents Sea is a shelf sea; depths are mainly between 200 and 4300 m although some banks are as shallow as 40-100 m. The southern half of the Barents Sea is characterized by Atlantic Water with temperatures of 3-6°C. At the Polar Front (at about 76°N), north-flowing Atlantic Water descends below Polar Water which is lower in temperature, yet lighter because of lower salinity. The Polar Front is well - defined in the western part of the Barents Seal, which there is a broad zone of mixing in the eastern half. North of Polar Front there is a marked pycnocline at 20-40 m depth which separates Polar and Atlantic waters; this pycnocline persists through the whole growth season of phytoplankton; i.e. mixing caused by wind is not strong enough to erode it. South of the Polar Front mixing characteristics are highly variable and dependent on wind. Around the shallow Svalbard Bank, waters may be thoroughly mixed the year round.

This talk deals with some of the basic features of the pelagic ecosystem in the Barents Sea and the effects of physical factors lupin the ecosystem, and it is based mainly on data from the Norwegian Research Program for Marine Arctic Ecology (Pro Mare), which lasted from 1984-1989. Comprehensive information will be given in the Pro Mare Proceedings in the journal Polar Research, which are to be published in early autumn 1991. thanks are due to dr. Dag Slagstad, SINTEF, Automatic Control, Trondheim for carrying out runs of his 3-D mathematical model of the physical oceanography and the plankton of the Barents sea, and to the Ministry of the Environment, The Norwegian Fisheries Research Council and The Norwegian Research Council for Science and the Humanities for financial support of Pro Mare.

The pelagic food web in the Barents Sea

The pelagic food web in the Barents Sea is based on phytophankton (the primary producers) which in turn are grazed by zooplankton (secondary producers, mainly copepods and krill) and which in turn are eaten by fish - in the Barents Sea mainly capelin. Capelin is a key species in the sense that both cod, seabirds, seals, whales, and man compte for it. It thus plays a role similar to that of krill in the Antarctic Ocean.

Energy and matter is fixed by the primary producers, and both flow through the ecosystem. As al rule of thumb, transfer from one trophic level to the next implies la loss of 80% or more of the energy and similar losses of matter. While energy is dissipated, matter (nutrients) excreted by the organisms may be reused by phytoplankton (production based on regenerated nutrients). With the large losses involved in each transfer between trophic levels, the ecosystem can hardly have more than 5-6 such levels.

The supply of excreted nutrients from organisms is always so small and combined
with such high grazing pressure that large algal biomasses cannot be sustained. Typically, ecosystems based on recycled nutrients are extremely oligotrophic (cf subtropical oceanic gyres). Eutrophic systems, in contrast, are based on "new"nutrients, i.e. nutrients brought into the system from deep waters - which implies that the pycnocline has to be eroded at regular intervals - or very close to land: from terrigenic sources including pollution. It is important to be aware that only systems with an adequate supply of "new" nutrients are "harvestable", i.e. tolerate fishing and hunting, and only such systems are climatologically relevant in that they allow sedimentation of large amounts of carbon fixed by phytoplankton.

For each tropical level we in principle have that, neglecting lateral and vertical transport of organisms, $dB/dtl = (\mu - d)$, where dB/dt is the time-dependent change in biomass, μ is the specific gross growth rate and d is the death rate. By coupling such equations for each trophic level and describing the rates as a function of environmental variables, al dynamical ecosystem model can be constructed. The equation states that the change in biomass with time is a function of the difference between growth (gain) and death rate (loss). Logically, environmental variables first affect the rates, and changed rates then affect the size of the standing stock. Thus changes in standing stocks are secondary effects of the environmental impact. Such models also imply that if only variations in standing stocks are known (as in most monitoring programmes), cause-effect relationships cannot be determined: did a standing stock decrease because the growth rate decreased or because the death rate increased? to answer such questions, which are urgent of the management of biological resources, at least one of the rates has to be know in addition to the standing stock.

As a rule of thumb, there is more biomass the lower the trophic level in the Barents Sea. As a very crude average, phytoplankton constitutes about 2 tones of carbon per km^2 and zooplankton about 3 tonnes; Average stocks of capelin and cod, however, constitute only 400 and 300 kg tonnes carbon per km^2, respectively, and for whales the biomass in terms of carbon is about 100 kg km^2. Seals are down to about 20 kg, seabirds about 1 kg, and polar bears represent only 0.07 kg carbon km^{-2}. For comparison, the population densities of humans in Norway and Japan correspond to 80 and 1600 kg carbon km^{-2}, respectively.

The seasonal phytoplankton cycle

For a phytoplankton cycle start in spring there has to be an ample supply of both plant nutrients and light. The ambient nutrient concentration depends on the difference between the supply of nutrients by vertical mixing and the consumption by phytoplankton and bacteria. In winter, consumption of nutrients by organisms is negligible, therefore concentrations in the upper layer remain at a high level; i.e. about the concentrations in deep waters. Winter concentrations of plan nutrients in the Barents Sea are about the same as for the Northeast Atlantic in general: 9-14 mmol m-3 of nitrate, O.5-O.6 mmmol m-3 of phosphate, and 4-5 mmol m-3 of silicate. There are only trances of ammonia in winter because of little biological activity. These figures are among the lowest for polar and boreal seas in winter and are to be regarded as "new" nutrients. Winter concentrations of nitrate and phosphate in the Bering sea and the Antarctic Ocean are about 2 and 3 times higher, respectively, than in the Northeast Atlantic, and silicate concentrations are event higher (up to 20 times in the Antarctic Ocean). These regional differences may be related to the age of the deep water; e.g. the waters in the Northeast Atlantic may reflect that the neighboring Norwegian Sea and, in part, the Barents Sea itself, produce their own bottom waters which thus are young and little enriched with nutrients.

The ice cover, which is of main importance north of the Polar Front, affects the development of the spring bloom. Ice, particularly when snow-covered, is opaque enough to prevent growth of plankton in the underlying water masses (light limitations). When, however, the ice melts, both light and nutrients are suddenly in ample supply, and at the same time the meltwater forms a well-defined upper water mass with lowered salinity; i.e. the depth of mixing is reduced to only 20-30 m near the ice edge. This ensures an optimum light regime so that the spring bloom starts almost explosively. The ice edge phytoplankton bloom may exhibit standing stocks as high as 8-15 mg m-3 in terms of chlorophyll a and may, provided optimum light, reach growth rates as high as O.6 d-1 at -0.5°C. Ice edge blooms, however, will have a short duration at any given locality - presumably less than 2 weeks - because they cannot be sustained beyond the point of depletion of the winter nutrients in the upper layers.

While the ice edge retreats northwards towards summer, ever exposing new nutrient-rich waters to strong light, the ice edge bloom trails it as a bank of 20-50 km width. This implies that the farther north, the shorter the growth (open water) season. To the extent the ice edge is well-defined (which it frequently is not), the ice edge bloom may be regarded as belt of concentrated biomass which sweeps the Barents Sea in Northward direction during the first half of the growth season. It offers local organisms one albeit fat meal per year, while organisms able to trail the ice edge bloom may have one long continuous meal.

Without doubt, the depth of vertical mixing is one off the major environmental variables for the timing and magnitude of a spring bloom. In the southern (Atlantic) half of the Barents Sea where waters are permanently open, the depth of mixing is usually as large as 40-60 m, which in turn implies less light to the algae relative to near the ice edge. Spring blooms may therefore develop later - a week or two -l and last longer. this, however, enhances the probability, relative to near the ice edge, that maximum phytoplankton and zooplankton stocks coincide, which in turn ensures that a large part of the phytoplankton bloom with be grazed.

The sinking fraction of the spring bloom algal biomass may constitute 50->80% of the produced matter, depending on to which extent part of the production is grazed by zooplankton. In a sense there is a "competition" between grazing and sedimentation; i.e. between "harvestable" and climatologically relevant production, although much of the grazed production also sinks in the final end, for instance in the form of fecal pellets.

After the winter nutrients have been consumed, further growth is regulated by the immediate nutrient supply. North of the Polar Front, where the pronounced pycnocline in ice-free waters remains until the end of the growth season, transport of nutrients to the upper mixed layer from below is negligible. The primary production is therefore regenerative and minute for the rest of the year. Standing stocks in the shallow mixed layer are usually <0.5 mg m-3 in terms of chlorophyll a. Instead there is a marked chlorophyll a maximum layer of 2-5 m thickness near the pycnocline (at 25-40 m depth), alt times with >20 mg chlorophyll a m-3. this layer is dominated by shade-adapted chlorophyll-rich cells which grow slowly because of light limitation and therefore consume little of the "new" nutrients available at the pycnocline. As a consequence, the only "new" production of respectable magnitude north of the Polar Front is represented by the spring/ice edge bloom.

South of the Polar Front, wind may cause mixing and transport of nutrients up to the illuminated layers more or less frequently after the spring bloom of phytoplankton. Vertical mixing, however, is a double-edged sword; on one hand deep mixing is necessary to bring "new" nutrients to the surface layers, on the other hand deep mixing ruins the light regime for the phytoplankton. The ideal condition might therefore constitute cycles of alternating deep mixing and stability. Periodic winds caused by the passage of atmospheric low pressures may do just that. A passage of an atmospheric low pressure begins with strong winds for 3-5 days (deep mixing: nutrients brought to the surface flayers) followed by 2-4 days of relatively calm weather (stable waters: phytoplankton growl and consume the nutrients). When the nutrients have been depleted, the next cycle starts, etc. The mathematical model for the Barents Sea indicates that winds are indeed important for the primary production: In the southern half, assuming no wind, primary "new" production in March-July is only 50 g C m^{-2}, which is about the magnitude of "new" production north of the Polar. Front where wind-driven mixing is not strong enough to erode the shallow and very distinct pycnocline. Model runs, however, based on wind data for 1983, predicts a "new" production for March-July of about 80-100 g C m^{-2}, i.e. twice as much. considering that the model predicts a spring bloom which is delayed by one month with wind relative to without because of the deeper vertical mixing, the favourable effect of wind on "new" production after the spring bloom is obvious. As a concluding remark, I might say that wind and weather, through their effects on the depth of mixing and the light regime are, together with grazing and sedimentation, the most important factors in controlling primary production and algal biomass in boreal and polar waters.

Prof. Manuel M. Murillo

Within the context of the Anton Bruun Lectures, I now have the honour of presenting Professor Chao Jiping from China. Dr. Chao obtained his PhD from the Meteorological Department of Nanjing University. Since 1989 he is Professor and Director of the National Centre of Marine Environmental Forecasts (SOA). Professor Chao Jiping has also occupied posts in several universities and institutes in China and was a visiting scientist at Princeton University. His work includes a wide spectra of themes in the area of meteorology including aspects of dynamics and circulation and also the numerical prediction of climatical conditions. In today's presentation, Professor Chao Jiping will refer to some of the results of his research and, in particular, the numerical system of real-time prediction related to the marine environment. I have the honour of asking Dr. Chao Jiping to begin his presentation.

3. The Real-time Numerical Forecasting `System for Marine Environmental Elements in China

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Summary

Like other countries along the ocean coast in the world, China is being challenged by the damages caused by severe oceanic events, such as storm surges, severe waves and sea ice. It is therefore of primary significance in China to investigate marine modelling of various time-scales and to improve the method of short-time scale prediction in recent years. A numerical prediction system including a method for decoding GTS data, objective analysis, atmospheric models combined with boundary layer model, storm surge models and sea wave model, has been established since January 1989.

Now, the predictors can receive reference from our numerical modelling products for doing the routine forecasting. Some numerical forecast products, such as sea ice during the winter season, are being directly issued to users.

The sea wave of the WAM model has been introduced into this system and connected with drive by seasurface wind given by a five-level atmospheric model for forecasting the sea waves in the area from 15 N to 45 N and from 105 E to 155 E.

A two-dimensional and non-linear storm surge model has been used for modelling surges along the coast of China. Also a moving nested barotropic atmosphere model and an analogy scheme have been adopted to forecast the track and the moving speed of typhoons. The sea surface pressure and stress fields are calculated based on the structure of the idealized typhoon field. The predictions of surge elevations and depth-averaged currents in the areas of the China Sea are obtained by using the storm surge model with these fields. A new baroclinic typhoon prediction model has been developed and will be connected with the storm surge model. The above tide-level atmospheric model with a boundary layer model is also connected with surge model to forecast the water elevations and currents caused by cold-wave and/or extratropical cyclones during the spring and winter seasons.

The detail structure of our models and the results of forecasting will be introduced by a report.

Abstract

The real-time numerical forecasting system for marine environmental elements including ocean wave, sea ice, storm surge, coastal current and sea surface temperature is presented. The introduction deals with the routine model of waves and storm surges in particular and show some results of forecasts.

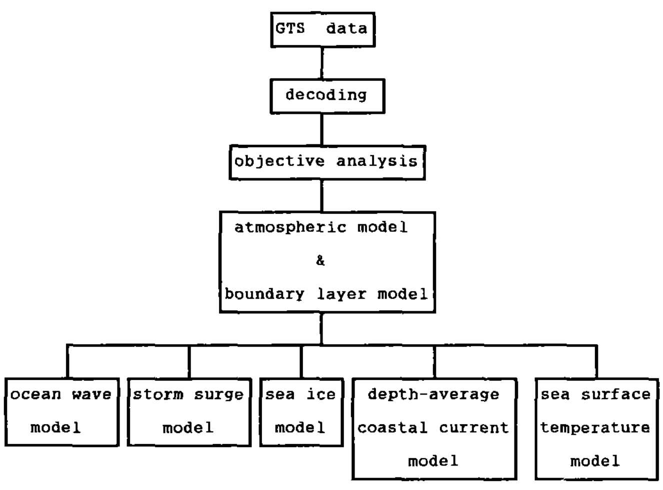
It is indicated that the most difficult one for real-time numerical forecasting is shortage of data both atmospheric and oceanic on the sea. An urgent task, therefore, is to improve the density and accuracy of oceanic data, especially to allocate more buoys and make further advances on the oceanic satellite remote sensing system.

Introduction

With the increasing needs of marine exploration, traffic, engineering, environmental protection and other activities, it has become urgent to set up a modern, objective and quantitative numerical forecasting system for marine environments in China. Therefore, a quasi-routine system has been established initially which started running on the computer system in January 1989 in the national Center for Marine Environmental Forecasts (NCMEF).

This routine numerical forecasting system consists of eight parts,they are: data decoding, objective analysis, atmospheric model, ocean wave model, sea ice model, storm surge model, depth-average coastal current model and sea surface temperature model. The data are received from the Global Telecommunication System (GTS), tidal stations along the coast of China and several buoys. An overall flow chart of this system is shown in Fig.1. It takes 90-mins of CPU time on the computer Cyber 180/840 for running the system for 72 hr forecasting. Below, is an introduction to the routine models of waves and storm surges in articular and show some results of forecasts.

Figure 1:
The flow chart of the numerical forecasting system in NCMEF.



Ocean wave forecasting

The third general wave model [WAMDI(1988)] was introduced and used for forecasting in the near-shore shallow water region of the China Sea. the used wave spectrum equation is

$$\frac{\partial F}{\partial t}+\frac{1}{Cos\phi}\frac{\partial}{\partial\phi}(\phi\cos\phi F)+\frac{\partial}{\partial\lambda}(\lambda F)+\frac{\partial}{\partial\theta}(\theta F)=S$$

where F is the wave spectrum, $\phi=d\phi/dt$, $\lambda=d\lambda/dt$ and $\Theta=\Theta_{gc}+\theta_D$, Θ_{gc} and Θ_D are the variations of the wave direction caused by the great circle reflection and topographic reflection respectively. The wind forcing, nonlinear interaction, dispersion process and bottom friction effect are involved in the source functions on the right hand side of Eq.(1)

The forecasting area is 15° N-45° N, 105° E-141°E on a mesh of 2° x 2°. The time-integral is by a implicit scheme, the interval of time-step is one hour, the resolution of frequency is $\Delta f/f=0.1$ and the resolution of direction is $\Delta\Theta=30°$.

The forcing wind fields fare obtained from a short-range numerical weather prediction model with an atmospheric boundary layer model. The 5-level primitive equation model with the σ-system of coordinates are used, in which large-scale condensation, convective adjustment, orographic effect and boundary layer parameterization are involved. The limited area model with grid interval of 190K.5 Km is nested in one way in the hemispheric model with the mesh of 381.0 Km. The finite difference scheme with conservation of total energy and mass is adopted. the lowest layer (σ=0.82-1.00) of the 5-level model is taken as the boundary layer,which is divided into two sub-layers, surface layer and Ekman-layer. The effects of thermal stratification and baroclinity on wind distribution are taken into account. Based on the boundary layer resistance law, the boundary layer model is connected with the atmospheric model for forecasting the sea surface winds.

The testing forecasts in the past two years show that the wave model connecting with the above model can provide a reference for the routine forecasting of wind waves in the China Sea. According to the atmospheric process, the forecasting results of the wave model are satisfactory for the waves caused by atmospheric cold-wave and cyclone moving eastward from the continent into the sea but not always satisfactory for the waves caused by typhoon. The two cases of prediction are given as follows:

(1) The case of atmospheric cold wave

Fig.2 shows the numerical forecasting wave fields caused by the cold-air moving southward on Feb.1, 1989. From the figure, we can see there are two centers of rough sea with significant wave heights of 3-3.5m and 2.5-3m. One is in the South China Sea and the other, which is getting intensive, is in the ocean on the east of the Philippines. Meantime a moderate sea with 2-2.5m

Figure 2:
The numerical forecasting wave field for 48-hr on 1 Feb. 1989.

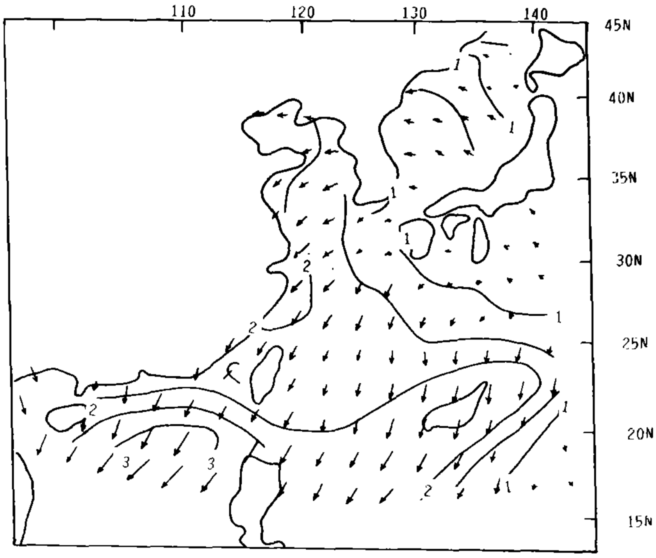
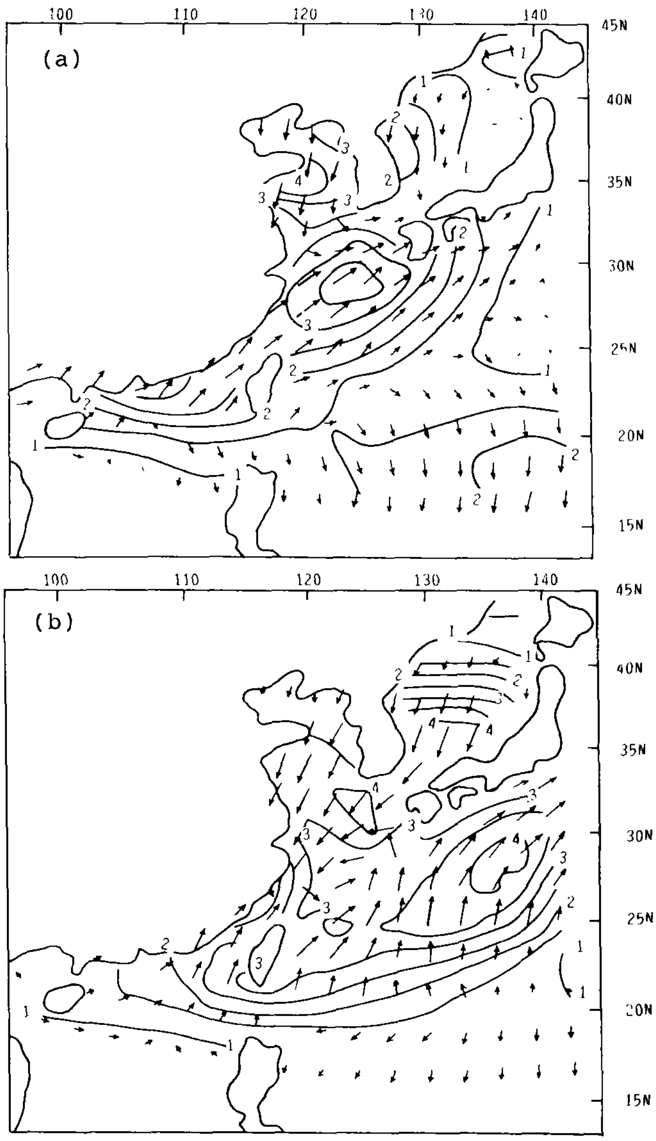


Figure 3:
The numerical forecasting wave fields for 36-hr on 15, and 16 Feb. 1989.



high can be also seen in the Japanese Sea. From ship observations at OO GMT of the 2nd and 3rd February, there was a rough sea with 4-5m high in South China Sea and a rough sea with 3m high in Japanese Sea.

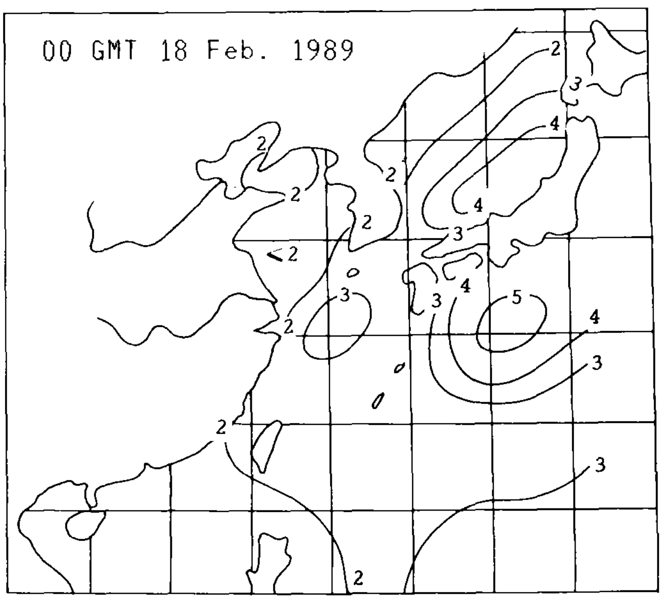
(2) The case of cyclone

The wave model gave a fairly good forecast for the sea wave caused by the cyclone moving eastward during the period of 15-18 February 1989. A rough sea with 3m high, which strengthen with moving north-eastward, was observed in the area to the East China Sea at OO GMT of 16 February. Fig. 3 gives the evolution of the forecast wave fields. It shows that the moving direction of the wave region and the intensity of waves are agreeable with the observation. Fig. 4 shows the observation of waves at OO GMT of 18 February.

It turn out that the forecast results and the observations are in reasonable agreement except that the intensity of forecasts is slightly weak.

The forecasting area shown above will be further expanded southward up to the Equator to cover the whole South China Sea and the forecasting range will be extended from 2-3 days to 4-5 days in the near future.

Figure 4:
The observed wave field at 00 GMT on 18 Feb. 1989.



Storm surge forecasting

A two-dimensional nonlinear storm surge model has been used for forecasting surges along the coast of China.

The water is assumed to be homogenous and incompressible. The prediction equations for the elevation of sea surface and depth-mean current are

$$\frac{\partial \vec{V}}{\partial t}=-(\vec{V}\cdot\nabla)\vec{V}-f\vec{K}\times\vec{V}-g\nabla\zeta-\frac{1}{\rho}\nabla P_a+\frac{\vec{\tau}_a}{\rho_D}-\frac{\vec{\tau}_b}{\rho_D} \quad (2)$$

$$\frac{\partial\zeta}{\partial t}=-\nabla\cdot(D\vec{V})$$

where

$$\vec{V}=\frac{1}{D}\int_{-h}^{\zeta}\vec{V}dz$$

$$D=\zeta+h$$

ζ is the deviation of the elevation of the sea surface from equilibrium state, h, the undisturbed water depth which is taken from the charted depth, the density of sea water, P the atmospheric pressure on the sea surface, he bottom stress which is supposed to be proportional to the quadratic value of depth-mean current. The wind stress on the sea surface which is expressed as:

$$\vec{\tau}_A=\rho_A C_D|\vec{V}_a|\vec{V}_a$$

where ρ_a is the density of air on the sea surface and C_D the surface drag coefficient which is taken as $2.6X10^{-3}$. V_a is the wind vector over the sea.

The computational domain covers the south China sea, the East China Sea, the Yellow sea and the Bohai sea. The Arakawa's B-type grid with the interval of 0.125° in latitude and in longitude and the split explicit scheme with the time-step of 2 mins and 12 mins are used in the model. According to the idealized typhoon structure, the atmospheric pressure and wind field V. are estimated by using typhoon parameters including center position, intensity, maximum wind speed and its radius. The typhoon positions are forecasted by using the typhoon prediction system including a moving nested barotropic typhoon model and an analog scheme, other parameters are obtained from the empirical predictions.

During the trial forecasting, serious disaster was caused by the storm surges of Typhoon 8923 along the coast of Zhejiang Province. The peak surge met the highest tide just when Typhoon 8923 landed near the tidal station of Zhejiang Province Haimen on September 15, 1989. The highest tidal level rose to the level of 689cm and exceeded the warning level by 148cm. The dashed line in Fig. 5 shows the predicted track of Typhoon 8923. The forecast fields of surge elevation and the depth-mean currents are obtained from the storm surge model, as shown in Fig. 5. The peak of 122cm given by the numerical predication is quite close to the observed peak at the station Haimen except a phase leg, as shown in Fig. 6, for a slower moving speed of the predicted typhoon than that of the observed. But the predicted peak by the empirical-statistical methods is not over 50 cm. The predicted elevation conforms with that observed at the station Zhenhai (Fig. 6).

A hindcasting case is given in order to check the forecasting capability for severe storm surges. Typhoon 8007 hit the coast of Guangdong Province and the sea encroached upon the land of Leizhou Peninsula in 1980. Fig. 7 shows the 24hr forecasting fields of surge elevation and depth-mean current in the region of the South China Sea. A sequence of forecasting charts clearly shows the surge development induced by Typhoon 8007. From Fig. 7 it is obvious that there are strengthened currents westward along the coast of Guangdong Province which then turn southward. It causes sea surface elevation to rise sharply along the east coast of Leizhou Peninsula during 22 July 1980. Fig 8 shows that the forecasting and simulating elevations at the grid points agree closely with the observation at the tidal stations near by. The observed data were suspended at *the station Zhanjiang for the tide gauge was broken down* at 09 GMT (01 BLT) 22 July. The star sign notes the visual estimation from the mark of sea water on the wall of coastal buildings. The predicted peak values and their appearance time are in conformity with the observed information.

Figure 5:
The predicted track of Typhoon 8923, the surge elevations and the depth-mean currents.

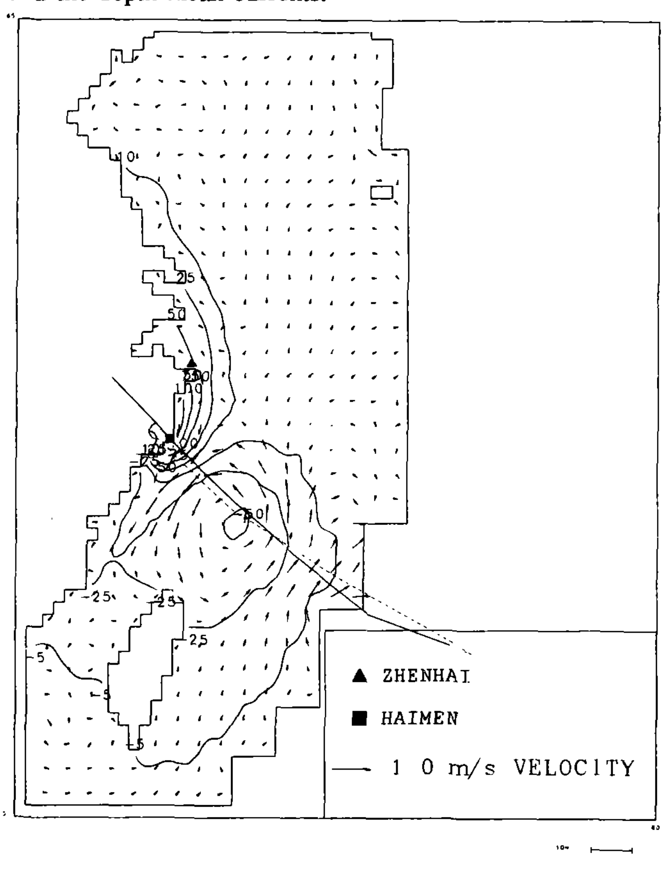


Figure 6:
Comparison between the predicted surge elevations of Typhoon 8923 at grid points (dashed lines) and the observed at the tidal stations bear by (solid lines). The observed data were suspended at the station Haimen for the tide gauge was broken down.

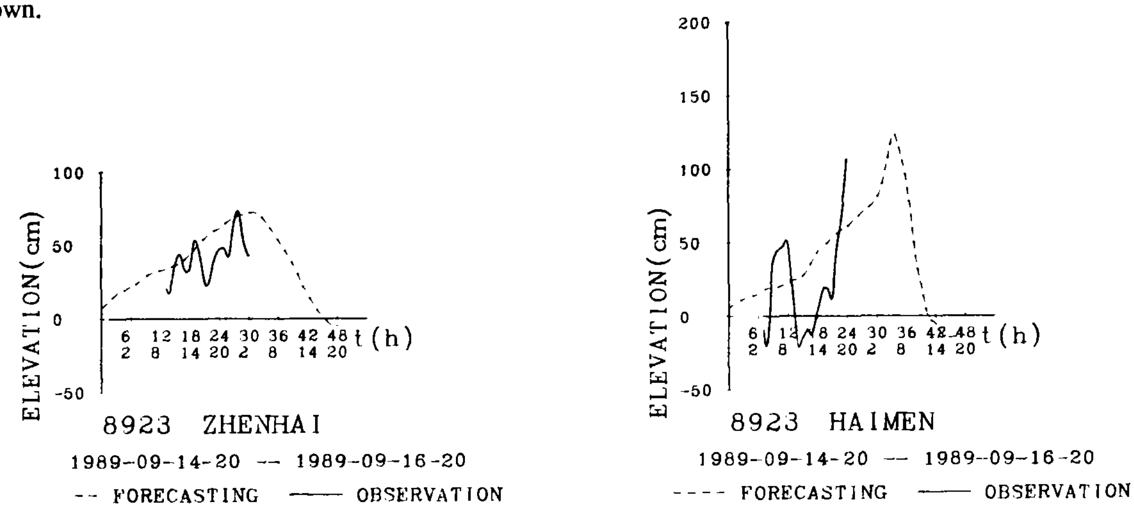


Figure 7:
The Predicted track of Typhoon 8007, the surge elevation and the depth-mean currents.

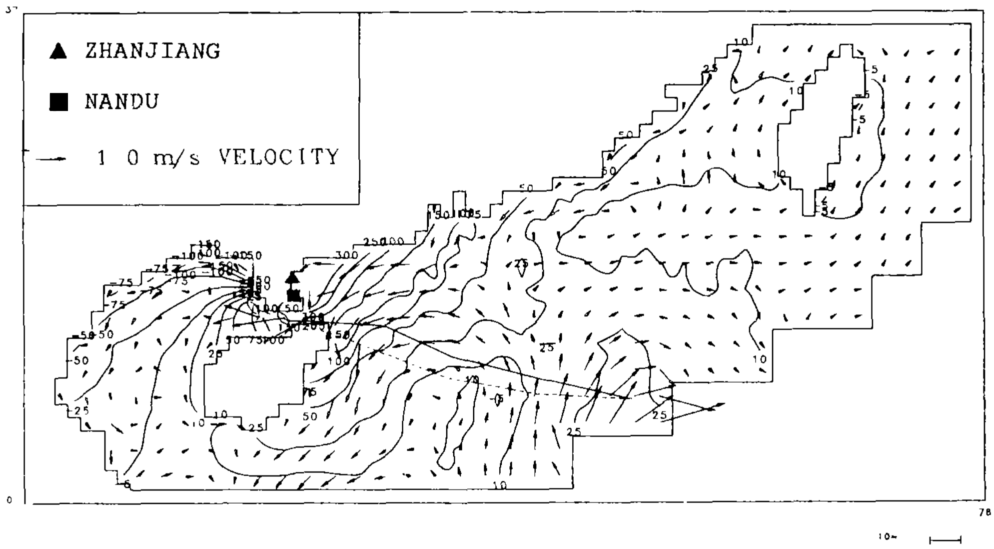
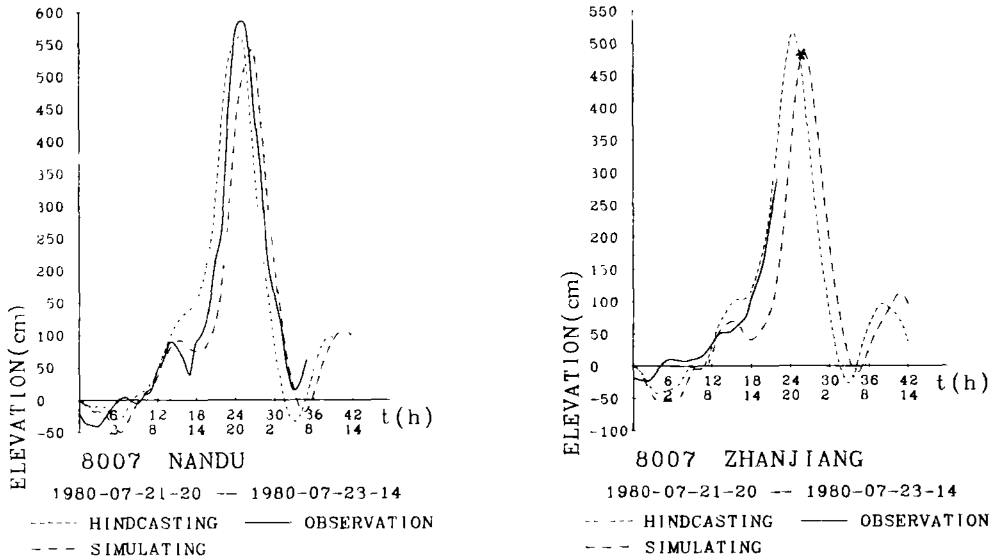


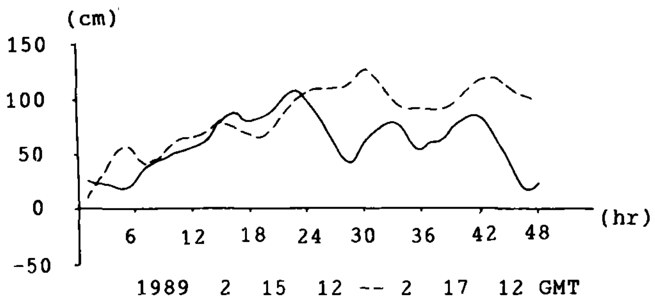
Figure 8:
Comparison between forecasting and simulating (dashed lines) elevations of Typhoon 8007 at grid points and observations at the tidal stations near by (solid lines).



A new numerical typhoon forecast system in which a baroclinic typhoon prediction model,the barotropic typhoon motion prediction model, the analog scheme and specialist system are included, has been proposed and will be connected with the storm surge model. A variational technique is used for improving the forecasts of the typhoon wind-pressure fields.

The case of atmospheric cold-wave: A 5-level numerical weather prediction model with a boundary layer model is connected with the surge model to forecast the water elevations and currents caused by the cold-wave and/or the extratropical cyclone during spring-winter. The cold high moved near the Bohai Sea and caused the water level to rise rapidly in the Laizhou Bay of the Bohai Sea during 15-16 Feb., 1989, as shown in Fig. 9. The dashed line is the forecasting elevation at the station Xiaying. The numerical forecasting value quite agrees with the observation. It is shown clearly from the numerical weather prediction results that the deviation after 14hrs is related to that the forecasting moving speed of the high is slower than the real one. Fig. 10 shows the forecasting fields of water elevation and currents caused by the cold-wave.

Figure 9:
Comparison of the forecasting elevations (dashed line) with the observation (solid line) at the station Xiaying.



Verification procedures have been used to check the forecasting system and make objective assessment of the models. Standard deviation of error, weighted root-mean square error by surge peak and absolute correlation between forecasting and observational elevations at tidal stations under the influence of storm surges were estimated and they are, respectively, 30cm, 37cm and 65% on the average for the testing forecasts in 1989.

Remark:

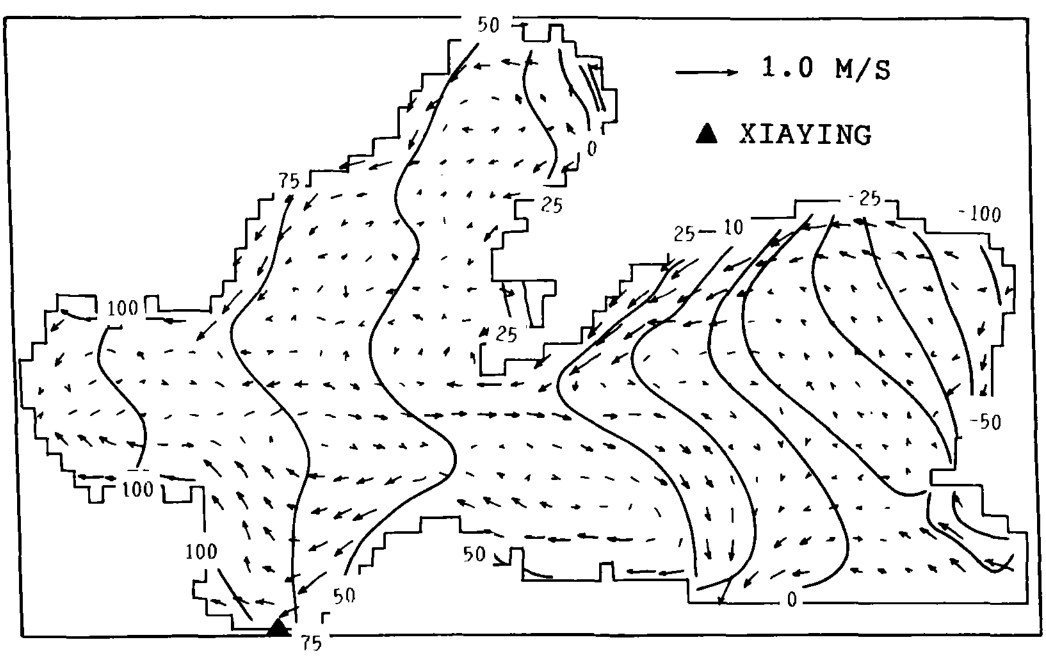
In brief, because this routine numerical forecasting system was established not long ago, there are still many problems need to be solved, the most difficult one is short of data both atmospheric and oceanic on the sea, it is still hard to improve the reality of the initial field even a good objective analysis was used. Consequently, it is extremely necessary to improve the density and accuracy of oceanic data, especially to allocate more buoys and make further advances on the oceanic satellite remote sensing system so as to get the data for the four-dimensional as simulation.

Apart from providing the numerical forecasting products to the operational forecasting group as a reference to the routine forecasts by conventional methods, now we are going to issue them to users directly in several ways.

Acknowledgements

The authors would like to thank Prof. Yi ZengXin, Mr. Chen Bin, Mr. Du Jian Bin, and Mr. Zhang ZhanHai for their help in completing this paper.

Figure 10:
The 36-hr forecasting fields of elevations and currents in the Bohais Sea and the North Yellow Sea, at 12 GMT 15 Feb. 1989.



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Discussion

Question: Is the entire coast of China, so charted with respect to bottom topography and details so that you are able to forecast storm surges along the entire coast when a typhoon comes? As you know it takes a fare amount of information, well in advance, to forecast a storm surge when a typhoon arrives. You have to have the bottom topography in your models, you have to have the details of the coast in your models, etc. Do you have all of this for the entire coast of China now?
Answer: The typhoon wind force is very difficult to predict for us, so right now we only predict the track and position of typhoons, not the wind force. The wind force and the atmospheric pressure we get that by a theoretical structure model - it is very difficult to do that. But in the next thirty years... no. Right now, we have five layers a model. We want to predict all the typhoon structure but it is not easy to do that. In particular, data is short for the China Sea. So I hope that the developing countries establish some system of oceanic supplies.

Prof. Manuel M. Murillo

Are there any more questions for Dr. Chao? No. I would would like to thank Dr. Chao for his presentation. Equally I would like to take this opportunity to also thank Drs. Mooers and Sakshaug for their presentations today within the field of the Anton Bruun Lectures.