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Physical Oceanography: A Brief Overview for Statisticians

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Abstract. Physical oceanography is the study of the physics of the ocean. As such, the discipline encompasses a very broad diversity of phenomena, ranging from the smallest space and time scales of order 1 second and 1 cm associated with vertical turbulent mixing, to the largest space and time scales of order centuries and 10,000 km associated with global climate variations. The processes occurring at different scales interact in very complicated ways. The multiscale characteristics of physical oceanographic data require sophisticated statistical analysis techniques to investigate a specific process and its interactions with other processes. Collaborative interactions between physical oceanographers and statisticians could potentially result in the development of new and innovative statistical techniques that could improve the present understanding of physical oceanography. The *Statistics and Physical Oceanography* report reproduced in this volume represents one element of an effort by the Office of Naval Research to stimulate more collaborations between the two disciplines. This introduction to the report provides a framework for understanding the context of the report. For the benefit of statisticians with little or no prior exposure to physical oceanography, this introduction also provides a brief survey of the general topics of physical oceanographic research, a description of the temporal and spatial scales of physical oceanographic data, and a summary of the demographics of physical oceanographers.

Key words and phrases: Physical oceanography, geostrophy, general circulation, wind-driven circulation, thermohaline circulation, mesoscale variability, fine structure, microstructure, internal waves, turbulence, climate, modeling, data assimilation, time series, frequency power spectral density, wavenumber power spectral density, Lagrangian, Eulerian.

1. INTRODUCTION

It is perhaps surprising to non-oceanographers that the physical characteristics of the ocean are poorly described, even after a century of effort. Because of the vastness of the ocean (an average depth of 4 km and a surface area of 90 million km^2, accounting for 70% of the surface of the earth) and because the most energetic variability (the so-called mesoscale variability, which is the ocean analog of weather systems in the atmosphere) has spatial scales of tens of kilometers and time scales of weeks, the ocean is spatially and temporally undersampled by all existing and likely future data sets. The historical oceanographic data set is therefore insufficient for addressing many of the important questions in oceanography. Sophisticated statistical analysis techniques are essential for quantifying the limitations of the existing data and for drawing defensible inferences about the nature and causes of the various signals that are imbedded in the observations.

Paradoxically, although oceanographers are in need of much more data, they are at the same time overwhelmed with an almost unmanageable amount of data. For example, the world hydrographic data archive includes more than 5 million vertical profiles. Not all of these are of high quality, however. There are approximately 500,000 high-quality open-ocean profiles of temperature and salinity (from which density profiles can be calculated), and more than 3 million high-quality shallow profiles of temperature alone (Levitus, 1982, 1993). As shown in Figure 1,

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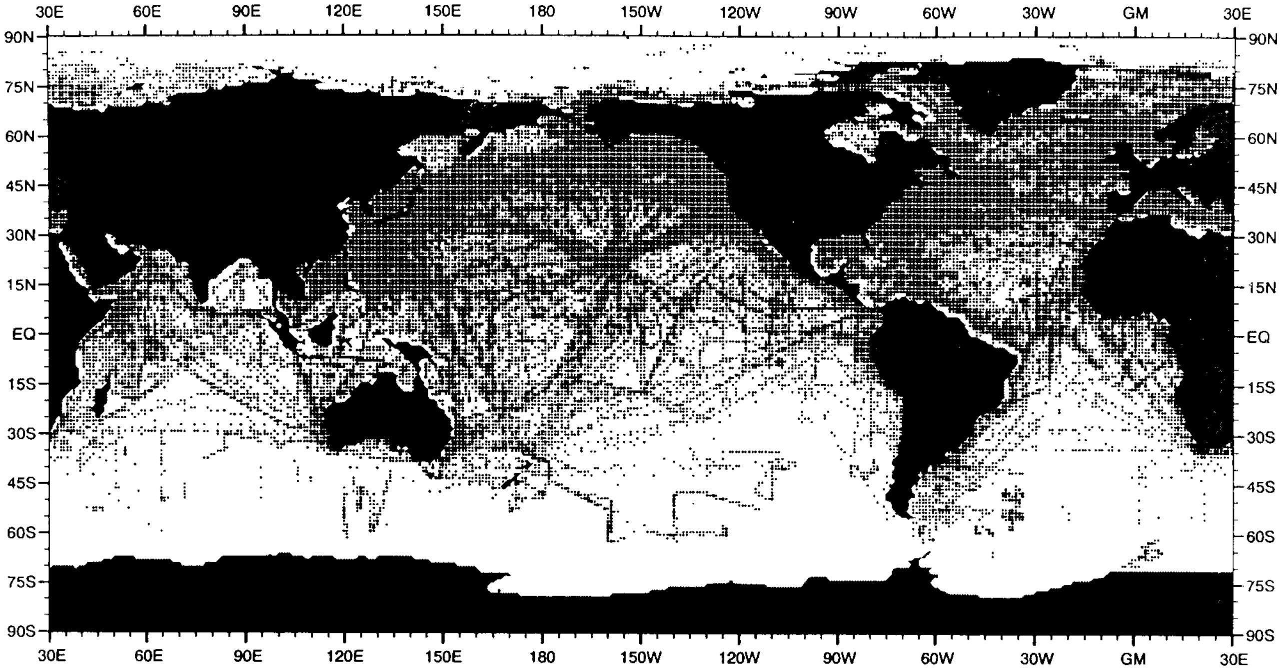
AUGUST SURFACE TEMPERATURE

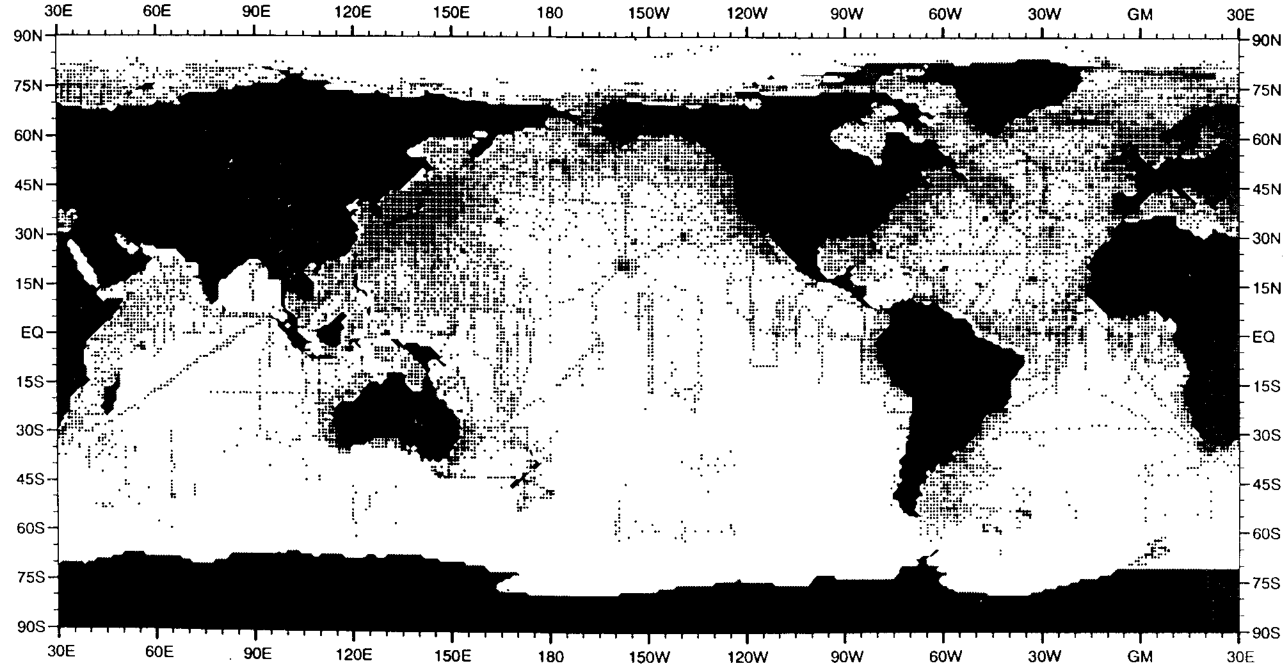
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FIG. 1. *Geographical distribution of* 1° *squares containing surface observations of temperature (upper) and salinity (lower) compiled since 1900 for the month of August. A large dot indicates five or more observations in the* 1° *square, and a small dot indicates one to four observations in the* 1° *square. (Courtesy of D. Johnson and S. Levitus, National Oceanic and Atmospheric Administration.)*

the geographical distribution of these data is biased in favor of the northern hemisphere and tends to be concentrated along specific ship tracks across the ocean basins. In addition, only about 20% of the temperature and salinity profiles extend deeper than 1 km and only a few percent extend to the bottom (e.g., Figure 2.1 of Worthington, 1981).

Although large in its own right, the extensive world hydrographic data set is but a small fraction of the total data available for oceanographic research. Other types of physical oceanographic data include time series of water velocity from current-meter moorings; the trajectories of surface drifters and subsurface floats; and time series of sea level and sea surface temperature at coastal locations. In addition, more than 100 million surface weather observations (winds, humidity and air temperature) have been archived globally since 1854 (Woodruff et al., 1987). These weather observations provide information about the surface forcing of ocean circulation that is crucial to physical oceanographic research.

Even without probing specific research topics, this wealth of data obviously offers endless opportunities for statistical analysis. Compilation of an all-encompassing list of relevant statistical techniques would be a daunting, if not impossible, task. In many cases, standard statistical techniques are inappropriate; the analysis techniques must be tailored to the specific scientific question of interest. A list of techniques would therefore be as rich and diverse as the variety of data types and research topics in oceanography. It is clear that oceanographic research could benefit from the expertise and experience of the statistical community. Moreover, the unique sampling characteristics of many oceanographic data sets and the spatial and temporal complexity of oceanographic variability demand development of new and innovative statistical analysis techniques, thus benefitting the statistical community by providing challenging new research topics. To date, however, there has been surprisingly little cross-fertilization between the two fields.

In an effort to stimulate more collaborations between statisticians and oceanographers, the National Research Council (NRC) recently produced a report highlighting seven broadly categorized topics of oceanographic research for which advanced statistical techniques would be very helpful. This report (entitled *Statistics and Physical Oceanography*, hereinafter referred to as S&PO) is reproduced in this volume for reasons explained at the end of Section 5. Although important statistical problems exist in all subdisciplines of oceanography (biology, chemistry, geology/geophysics and physics), the S&PO report restricts attention to physical oceanography. This is because of the limited expertise of the panel members who wrote the report and the timetable and report length constraints imposed on the project.

The focus on physical oceanography can also be justified on the basis that the development and application of statistical analysis techniques are somewhat more advanced in physical oceanography than in the other subdisciplines of oceanography. In large part, this has been driven by rapid technological advances that have allowed observations spanning a broad range of space and time scales. Simultaneously, there have been an intensive development of a theoretical foundation to explain the observations and a growing recognition of the importance of physical oceanographic processes in global climate variability. Statistical analysis has become essential for extracting information from these large volumes of physical oceanographic data and for developing an understanding of ocean processes through comparisons between theory and observations.

This introduction of the S&PO report attempts to provide answers to some of the questions about physical oceanography that are not addressed by the report, but are likely to come up for statisticians wishing to pursue research opportunities in physical oceanography. A "blueprint" of physical oceanography is provided in Section 2, including a summary of the demographics of physical oceanographers (see also the Appendix), a brief survey of the general topics of physical oceanographic research and a description of the temporal and spatial characteristics of oceanographic data. Because of space limitations, the treatment of these topics here is, unfortunately, too short to do them justice. A more detailed overview, including graphic examples of oceanographic data, is given by Chelton (1994).

In order to place the content of the report in the proper perspective, a background of developments leading to the writing of the S&PO report is given in Section 3. Details of the process of writing the report are documented in Section 4 and the report is described in Section 5. Some concluding remarks are offered in Section 6.

2. PHYSICAL OCEANOGRAPHY

2.1 Demographics

Although still very small compared with many fields of science, physical oceanography has grown rapidly over the past two decades. A detailed description of the demographics of physical oceanographers is presented in the Appendix. A brief summary is given here. The number of Ph.D.-level physical oceanographers in the United States more than doubled during the 1970's and increased by another 40% during the 1980's to the present total of about 400. This accounts for about 20% of the total number of Ph.D.-level scientists in all four subdisciplines of oceanography. About 2/3 of all physical oceanographers are employed by one of about 16 academic institutions and 1/3 are employed by one of about 8 federal laboratories; very few are employed by industry. Unlike most academic disciplines, teaching accounts for only a small fraction of the workload of most physical oceanographers in the academic sector. By the same token, few of them receive more than half-time institutional support. The primary work of most physical oceanographers has always been research supported by federal grants and contracts.

2.2 Synergism of Theory and Observations

Simply stated, physical oceanographic research consists of the study of the physics of the ocean. Remarkably, the broad range of physical oceanographic processes can, at least in principle, be described by seven equations: the three component equations for the conservation of momentum; equations for the conservation of density, temperature and salinity; and an equation of state relating density to temperature and salinity. These equations are presented and discussed in Section 1 of the S&PO report. The apparent simplicity of being able to distill all of physical oceanography down to a small number of equations is misleading. Because of nonlinearities and the inability to specify initial and boundary conditions completely, it is not possible to solve these equations explicitly. As discussed in Section 1 of the report, the complete equations must be simplified in order to gain some insight into the dynamics of fluid motion.

A primary objective of physical oceanographic research is thus to develop simplified theoretical constructs (models) and investigate their validity from observational data. In a few cases, theory has preceded observations of a physical oceanographic phenomenon. More typically, however, advances in theoretical understanding have been preceded and motivated by observations. Indeed, even today, new observational tools often lead to new discoveries and, in many cases, a revamping of physical oceanographic concepts. Subsequently, theoretical developments provide specific testable hypotheses to be investigated from further observations. Observations have thus been the foundation of nearly all physical oceanographic research.

2.3 Temporal Variability

The longest records of physical oceanographic data are hourly measurements of sea level from coastal tide gauges. Worldwide, there are now 35 tide gauge locations with data records longer than 100 years and about 575 locations with data records longer than 20 years (Woodworth, 1991). Because of their uniquely long record lengths, sea level data serve as an excellent example of the multiple time scales simultaneously present in physical oceanographic data.

The most energetic signals in tide gauge records are the tidal variations (Cartwright, 1977, 1993) with periods near 0.5 and 1 day for which tide gauges were originally designed. At longer periods, there are sea level variations on a wide range of other time scales, as summarized in detail by Chelton and Enfield (1986). These include variations on time scales on the order of days related to atmospheric forcing from storms and the propagation of long ($\gtrsim$ 100 km) coastally trapped waves; seasonal variations (predominantly annual and semiannual variability) associated with the steric effects of heating and cooling and nearshore ocean currents; and interannual variations with time scales of a few years, often in association with the El Niño phenomenon (Philander, 1990). The long-period sea level signal of most urgent concern environmentally is the underlying secular (i.e., monotonically increasing or decreasing) variation present in nearly all tide gauge records. Tide gauge data are the only available long-term measure of the ocean response to global warming (e.g., Barnett, 1984; Douglas, 1991).

There are also very large sea level variations at time scales shorter than the tidal periods. However, these signals are attenuated in tide gauge data by only allowing water to enter or exit the gauge slowly through a small orifice. At periods of order 10 seconds, the sea level variability is dominated by surface gravity waves. At even shorter time scales down to about 0.1 second, there are sea level variations from gravity–capillary and pure capillary waves (wind ripples) that play an important role in the transfer of momentum from the wind to the water.

The large variety of physical processes affecting sea level is characteristic of all oceanographic time series. The multiple time scales present in physical oceanographic data are best summarized by the *frequency power spectral density*, which displays the frequency distribution of the variance. A schematic spectrum is shown in Figure 2; actual examples of spectra from long data records can be found in Wunsch (1981). Oceanographic spectra are characterized by a continuum of variance over all frequencies with approximate power-law dependencies on frequency f (typically about f^{-2}) up to about 0.01 cycle s^{-1}. At higher frequencies, there is a broad peak centered at about 0.1 cycle s^{-1} associated with surface gravity waves, with a steep spectral rolloff of about f^{-4} at higher frequencies. Superimposed on this broad continuum spanning many decades in frequency are several narrow spectral peaks associated with tides and the seasonal cycle.

In velocity time series from current-meter data, there is also a spectral peak at the local inertial frequency of $2\Omega \sin\theta$ (where $\Omega = 1$ cycle day^{-1} is the rotation rate of the earth and θ is latitude), which is the natural frequency of oscillation for an impulsively generated disturbance on the rotating earth.

2.4 The General Circulation

The circulation associated with the mean distributions of water mass properties is referred to as the *general circulation*. Theoretical developments in the early 20th century provided the basis for deducing the patterns of the general circulation from hy-

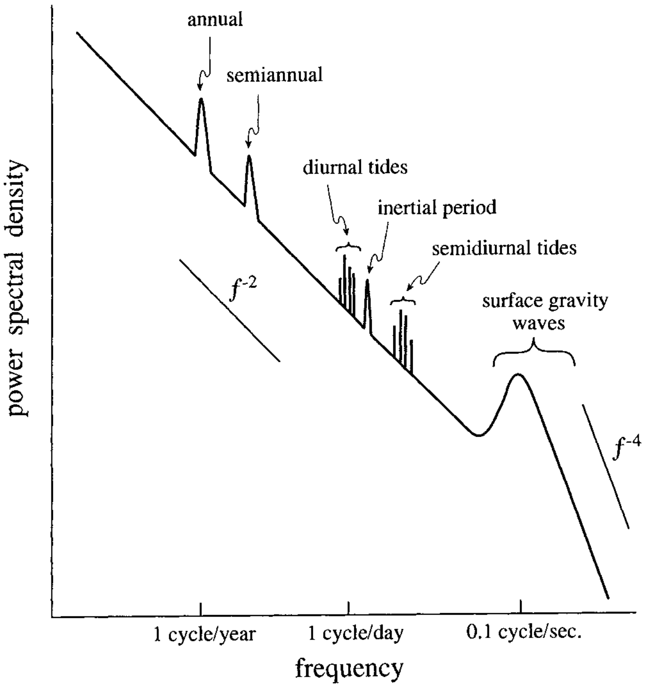

FIG. 2. *A schematic* log–log *plot of the power spectral density of an oceanographic variable. The various spectral peaks are labelled, and some frequencies are labelled along the abscissa. The inertial peak exists only in velocity data, and its frequency depends on latitude (see text).*

drographic data. A moving parcel of water in the rotating reference frame of the earth experiences an apparent force (called the *Coriolis force*) that is proportional to its velocity and directed perpendicular to the direction of motion. On large scales away from surface, bottom and lateral boundaries, friction can be neglected and the Coriolis force is balanced by an opposing horizontal pressure gradient force. This balance of forces (referred to as *geostrophy*) thus determines the water velocity; the geostrophic velocity is proportional to the cross-stream pressure gradient.

The horizontal pressure gradient in the ocean is supplied by a tilt of the sea surface and internal horizontal variations in density, which can be calculated from temperature and salinity. The vertical profile of horizontal velocity in the water column is then determined by the so-called geostrophic method (e.g., Pickard and Emery, 1990, pages 115–122) from horizontal density gradients calculated from pairs of hydrographic profiles. One of the outstanding problems of physical oceanography is that the total pressure gradient cannot be determined from the density structure alone. Density data only define the change in horizontal pressure gradient from one level to another, and hence the geostrophic velocity at one level relative to that at another. The absolute pressure gradient (or, equivalently, the absolute velocity) must be known independently at one level to determine the absolute velocity profile. The traditional method of addressing the reference-level problem of the geostrophic method is to assume that the velocity vanishes at some deep level (the so-called *level of no motion*). This depth is invariably chosen in a rather arbitrary manner.

Deep-ocean velocities are nearly always much weaker than near-surface velocities. If the interest is in upper-ocean velocities, the reference-level problem is therefore a relatively minor concern, as long as a deep reference level is used. A qualitatively adequate description of the general circulation in the upper ocean was thus developed over the first few decades of this century from exploratory surveys of the depth distributions of temperature and salinity.

The general circulation in the northern hemisphere consists of clockwise *gyres* between the equator and about 45°N and counterclockwise gyres at higher latitudes. Within each gyre, the flow is more intense and concentrated near the western boundaries of the basins, with surface velocities of about 100 cm s^{-1} . A much weaker return flow to balance the mass transported by the western boundary currents is broadly distributed over the eastern two-thirds of each basin. These return flows are somewhat intensified near the eastern boundaries, but the mean velocities are only about 10 cm s^{-1}.

The general circulation in subtropical latitudes of the southern hemisphere is similar to the northern hemisphere counterparts, except that the gyres are counterclockwise. Because the ocean basins are not closed south of 55°S, there are no closed gyres at high southern latitudes. Instead, there is an Antarctic circumpolar current that flows essentially unimpeded around the Antarctic continent with surface velocities of about 50 cm s^{-1}.

A dynamical explanation for the general features of the upper-ocean general circulation (referred to as the *wind-driven circulation*), including the westward intensification, was developed in a series of papers published in the middle of this century (Sverdrup, 1947; Stommel, 1948; Munk, 1950). The near-surface currents are forced by the surface wind stress, but not by the winds simply "dragging" the surface waters. The dynamically important aspect of the wind field is the *curl of the wind stress*.

Surface fluxes of heat and fresh water are also important driving forces for the ocean circulation. This is especially true for the general circulation of the deep ocean. Because of the intense cooling at high latitudes and the increased salinity from brine released in the formation of ice, more than 80% of all of the water in the ocean is of polar origin. This deep water formation occurs at only a few locations globally. The sinking water must be replaced by less dense surface waters from lower latitudes. The resulting overturning circulation is referred to as the *thermohaline circulation*.

The velocities of thermohaline circulation are too small to be deduced from hydrographic data. As described, for example, by Broecker and Peng (1982), the circulation patterns must therefore be inferred from the distributions of water properties such as temperature and salinity, and transient chemical tracers whose concentrations change from processes other than mixing (e.g., biological processes or radioactive decay). Each source of deep water has a unique combination of water properties that allows the water mass to be tagged and identified many thousands of kilometers from the source.

2.5 Mesoscale Variability

The prevailing attitude that developed by 1950 from the accumulation of hydrographic data over the previous 50 years was that there was very little temporal variability in the deep ocean. Except for moderate seasonal variability, it was generally believed that even the near-surface circulation was relatively constant and large-scale.

As a result of two new technological developments in the late 1950's, the understanding of the extent and importance of temporal variability underwent a rapid transformation. The first of these were the surface drifters and neutrally buoyant subsurface floats developed for obtaining *Lagrangian* estimates of water velocity (i.e., the velocity obtained by following the path of a parcel of water). The first deployments of floats in the late 1950's at depths of 2000 and 4000 m in the western North Atlantic yielded very surprising results: the floats moved at speeds in excess of 10 cm s^{-1} for periods of several days, which was an order of magnitude faster than was expected. These float observations had a profound influence on the direction of physical oceanographic research. The paradigm of quiescent deep-water circulation had to be abandoned, and the level of no motion concept became suspect.

The large float velocities were subsequently found to be the manifestation of what came to be known as *mesoscale variability*; the mean velocity at depth is generally small, but the instantaneous velocity can be large. The time scales of mesoscale variability range from weeks to months. The spatial scales span a broad range, but are dominated by the Rossby radius of deformation (e.g., Pedlosky, 1987), which is typically 20–50 km.

The availability of satellite tracking beginning in the 1970's greatly expanded the use of drifters and floats. Methods of interpreting Lagrangian measurements in terms of the *Eulerian* perspective (i.e., the velocity at a fixed location) that physical oceanographers are generally more interested in is an area of active research (e.g., Davis, 1991a, b).

The second major technological development that occurred in the late 1950's was the development of current meters able to measure water velocity autonomously. The earliest deep-ocean current-meter measurements verified the existence of energetic mesoscale motion throughout the water column. From the large number of long current-meter records that have accumulated over the past 30 years, it is now known that time-dependent current velocities arising from mesoscale variability are often an order of magnitude or more higher than the mean velocity associated with the general circulation. It is not uncommon to be unable to obtain a statistically stable estimate of the mean flow, even after averaging current-meter records over a year or more.

Satellite techniques developed in the last 15 years have greatly improved our understanding of the geographical distribution of mesoscale variability by providing unique perspectives that are not possible by any other observational technique. *A synoptic view* (i.e., simultaneous over a broad area) of mesoscale variability in the western North Atlantic is shown by the satellite infrared image of sea surface temperature in Figure 3. The Florida Current is readily apparent as the narrow ribbon of relatively warm water rounding the southern tip of Florida and following the continental shelf edge along the southeast coast of the United States. As the Florida Current leaves the shelf edge at Cape Hatters and becomes the Gulf Stream, very large *meanders* develop along the axis of the current. Some of these meanders pinch off, forming detached *eddies* and *rings*. Although images such as this are often taken for granted now, they provided the first clear understanding of the geographical characteristics of mesoscale variability in the late 1970's.

Because mesoscale eddies and meanders are in geostrophic balance, their surface manifestations are also apparent as sea level anomalies. The statistical properties of the spatial structure of mesoscale variability can therefore be quantified by the *wavenumber power spectral density* of sea level. This is easily obtained by satellite altimetry (e.g., Fu, Chelton and Zlotnicki, 1988) from sea level measured along the satellite ground track.

Spectra derived from altimeter data for six regions along 35°N in the North Atlantic are shown in Figure 4. It is evident that, just as the temporal variability in the ocean consists of a continuum of variance over all frequencies (Figure 2), the spatial variability consists of a continuum of variance over all wavenumbers. The spectra exhibit approximate power-law decreases in spectral energy with increasing wavenumber k. The steeper rolloff in the western hall of the basin ($\sim k^{-4}$) than in the eastern basin ($\sim k^{-1}$) and the flattening at low wavenumbers (wavelengths longer than the Rossby radius of defor-

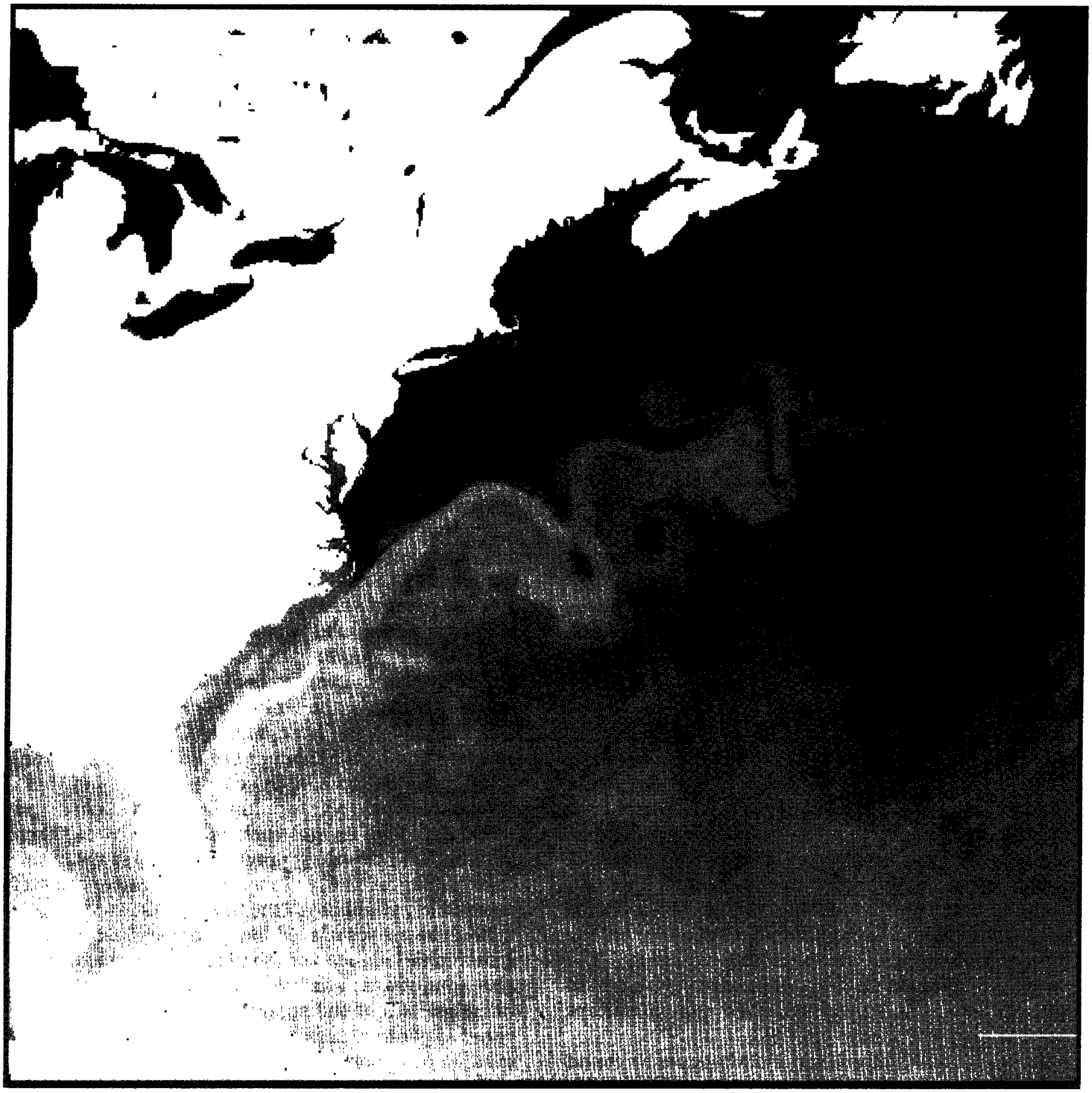

FIG. 3. *Satellite infrared image of sea surface temperature in the northwest Atlantic during June* 1984. *Colder water is shaded dark.* (*Courtesy of O. Brown, University of Miami.*)

mation shown by the arrows) in the western half of the basin may be related to differences in the eddy-generation mechanisms.

2.6 Vertical Structure

Prior to the early 1960's, information about the vertical distribution of temperature and salinity throughout the water column could only be obtained from Nansen bottles with reversing thermometers (e.g., Neumann and Pierson, 1966, pages 102–104). Temperature was measured in situ and salinity was determined on board the ship or in a laboratory by titration of a water sample collected at depth. By connecting Nansen bottles in series along a cable, the temperature and salinity were sampled at predetermined discrete depths. Typical bottle spacing consisted of 12 levels between the surface and 500 m and an additional 10 levels between 500 and 4000 m. Because Nansen bottle data were blind to

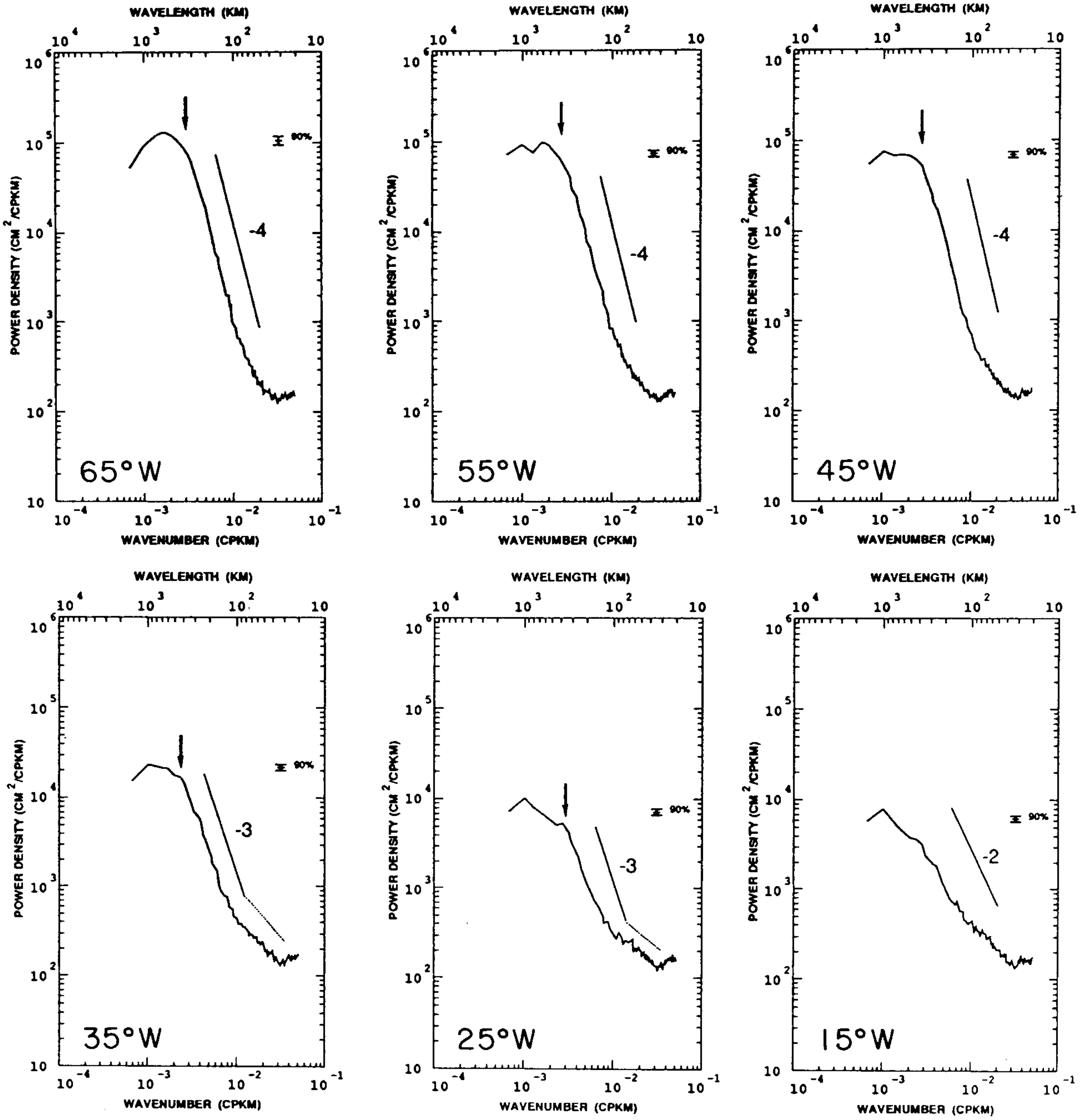

FIG. 4. *Wavenumber power spectral densities of sea level from the GEOSAT altimeter for six regions across the North Atlantic centered at* 35°N *and at the longitudes indicated in the lower left corner of each plot. (After Le Traon, Rouquet and Boissier,* 1990.)

features with vertical scales shorter than tens of meters, there was a tacit assumption that the smooth profiles that could be drawn through the discrete bottle samples of temperature and salinity were representative of the actual ocean.

A third technological development that matured simultaneously with the developments of float and current-meter technologies in the early 1960's made it possible to obtain high-resolution profiles of temperature and salinity. Like the change in direction of physical oceanographic research stimulated by the mesoscale variability revealed by the float and current-meter observations, the new information about the vertical structures of temperature and salinity marked the beginning of new focus of physical oceanographic research. As this technology continued to develop, it became apparent that there are signals on all vertical scales.

Profiling technology actually began with the development of a bathythermograph just prior to World War II for measuring shallow profiles of temperature. Continued development resulted in the expendable bathythermograph (XBT) (Rasmussen, 1963) that measures temperature by a thermistor at the tip of a probe and transmits the measurements electronically to the ship through a fine wire. Depth is determined from the known fall rate. Because of their low cost (about $50 each) and ease of deployment, XBT's continue to be used extensively for sampling the upper-ocean thermal structure. This accounts for the much larger number of temperature profiles than salinity profiles available in hydrographic data archives, as noted in the introduction (see Figure 1).

Continuous profiling of salinity was a more difficult technical challenge than temperature profiling. The first salinity–temperature–depth profiler (Brown and Hamon, 1961) determined salinity by its effects on conductivity. Continued technological improvements eventually resulted in the conductivity–temperature–depth (CTD) profiler described by Brown (1974). The CTD remains the standard instrument for hydrographic profiling today. The use of conductivity for determining salinity is so widespread and successful that the definition of salinity in terms of chlorinity determined by titration has been replaced by a new definition called practical salinity based on conductivity (Fofonoff, 1985).

From the very beginning, profiling data revealed far more complex structures in the temperature, salinity and density profiles than the many decades of Nansen bottle data had suggested. *Fine structure* (scales of 1–100 m) often develops when two surface water masses of slightly different density meet (e.g., Osborn and Cox, 1972). One water mass slides under the other along isopycnal surfaces (surfaces of constant density) to form interleaved temperature and salinity intrusions.

Another source of fine structure is *internal waves* that are observed virtually everywhere in the ocean. Unlike intrusive layered fine structure, the fine structure associated with internal waves is a time-dependent phenomenon that is not generally identifiable in a single vertical profile. The presence of internal waves becomes apparent in successive profiles at the same location as vertical variations in the depths of particular temperature or salinity values. Internal wave amplitudes of tens of meters are common and the periods of internal wave oscillations range from about 10 minutes in highly stratified regions to somewhat greater than 0.5 day.

The theoretical foundation for internal wave propagation in stratified fluids is well developed (e.g., Munk, 1981; Olbers, 1983). As a result of considerable observational and theoretical work, the importance of internal waves in the energetics of ocean circulation is now widely recognized. Recent work suggests that internal waves may play a key role in the transfers of energy and momentum at both larger and smaller scales by determining the horizontal turbulent mixing coefficients for mesoscale variability and by acting as a source of shear for vertical turbulent mixing that occurs on very short vertical scales. If this is the case, then internal waves may help determine the mean distributions of water properties on large scales.

The existence of velocity shears from internal waves and a variety of other sources introduces instabilities in the flow through nonlinear terms in the momentum and conservation equations. These instabilities generate *turbulence* that stirs and eventually mixes water properties much more efficiently than molecular diffusion. The importance of turbulence in the momentum equation is quantified by the nondimensional Reynolds number, which is the ratio of a typical nonlinear term to the molecular viscosity term. Scaling arguments based on representative values of these terms conclude that the ocean is nearly everywhere turbulent.

For "large-scale" distributions of water properties (scales larger than those over which turbulent mixing occurs), the effects of turbulence are usually parameterized in terms of "turbulent mixing coefficients" (also referred to as eddy diffusivities, or effective diffusion coefficients), as first suggested by Taylor (1915). The turbulent coefficients play the same role as molecular diffusivities in the momentum and conservation equations, but are several orders of magnitude larger (see Section 1 of the S&PO report).

From the smooth distributions of water properties evident in early Nansen bottle data, it was taken for granted that turbulent mixing exists throughout the ocean (Sverdrup, Johnson and Fleming, 1942); molecular processes are too slow to account for the observed large-scale patterns. Munk (1966) inferred the vertical turbulent mixing coefficient for heat from temperature profiles in the interior Pacific Ocean. The value obtained was three orders of magnitude larger than the molecular diffusion coefficient, clearly demonstrating the importance of the role of turbulence in the vertical mixing of heat. The vertical mixing coefficient estimated by Munk (1966) has subsequently been judged to be reasonable by large-scale numerical modelers, as it results in qualitatively accurate simulations of the temperature structure and circulation of the ocean.

As a result of continued technological developments in vertical profiling over the past 30 years, the vertical structures of temperature, salinity and horizontal velocity are now resolved down to the approximate 1-, 0.1- and 3-cm scales, respectively, where it is believed that molecular diffusion becomes dominant (Gregg, 1991). It is found that the largest mean squared gradients of these quantities occur at *microstructure* scales, defined to be vertical scales shorter than 1 m. A perplexing result is that the vertical turbulent mixing coefficient obtained from microstructure measurements is an order of magnitude smaller than that inferred by Munk (1966). This smaller value of the mixing coefficient has recently been independently confirmed from measurements of the time rate of change of the vertical spreading of chemical tracers injected in the ocean (Ledwell, Watson and Law, 1993).

Reconciling the discrepancy between the estimates of the vertical mixing coefficient obtained thus far from microstructure and tracer measurements and the order-of-magnitude-larger value required for realistic simulations in numerical models remains an unsolved problem. If the mixing coefficients obtained from observations are used in numerical models, the model simulations are not able to diffuse the upper ocean heating from air–sea heat flux. At present, it is not known whether this is indicative of inadequacies in the models or in the observational data.

2.7 The Role of the Ocean in Climate

The ocean plays a critical role in the long-term average global climate. The enormous heat capacity of the large reservoir of water in the ocean and the ease with which heat can be released to the overlying atmosphere moderate the temperatures of the lower atmosphere; the heat content of just the upper 3 m of the ocean exceeds that of the entire atmosphere. The ocean also plays a major role in *climate variability*. Because of the higher thermal and mechanical inertia of water, the time scales of ocean heat storage and transport are much longer than those of the atmosphere. Oceanic variability may therefore be the principal factor controlling climate variability on time scales of months to decades. Moreover, because it is the primary source of moisture for the atmospheric, cryospheric and terrestrial components of the hydrological cycle, the ocean also plays a critical role in controlling global patterns of precipitation and evaporation.

Much of present physical oceanographic research is focused on understanding the details of the roles of the ocean in short-term (months to years) and decadal *climate variability*. Because the scales of climate variability are so large, the trend in physical oceanographic research has been toward larger and longer-term programs than have ever been attempted in the past. This has necessitated an unprecedented coordination of a large number of individual investigations, both nationally and internationally, and has resulted in two major field programs.

The first of these is the *Tropical Ocean–Global Atmosphere* (TOGA) program, which began in 1985 (NRC, 1990). TOGA consists of a decade of atmospheric and oceanic observations in the tropical Pacific intended to improve the description and prediction of the El Niño–Southern Oscillation (ENSO) phenomenon (Philander, 1990). Coupled ocean–atmosphere numerical models developed as part of TOGA have successfully predicted the two most recent ENSO events (1987 and 1992) a year in advance (e.g., Cane, 1991; Ropelewski, 1992). Extending predictability to global patterns of rainfall and air temperature associated with ENSO is an area of active research.

The second international field program is the *World Ocean Circulation Experiment* (WOCE), which officially began in 1990 and will continue through 1997 (Needler, 1992). WOCE is a coordinated program to acquire the observations necessary to develop numerical ocean models suitable for prediction of decadal climate variability and oceanic meridional heat transport. The timing of WOCE was largely dictated by the launch of a series of satellites that are essential for obtaining global measurements of the ocean. WOCE also includes an intensive in situ field program intended to improve the global description of the general circulation of the ocean.

In recognition of limitations both in modeling and observing the ocean for studies of global climate variability, a great deal of emphasis in TOGA and WOCE is directed at combining models with satellite and in situ data through sophisticated *data assimilation* procedures (Ghil and Malanotte-Rizzoli, 1991; Bennett, 1992). The objective is to produce a better description of the ocean circulation than can be obtained from either the models or data alone. This is effectively achieved through an optimal weighted least squares combination of the model output and observations. The weightings applied to each component attempt to quantify statistically the inaccuracies of models and the incompleteness and measurement errors of observational data.

2.8 Summary

The wide variety of observational data that have become available over the past 50 years has revealed that ocean variability consists of a continuum of spectral energy over temporal scales ranging from about 1 second to centuries and spatial scales ranging from about 1 cm to 10,000 km. The variability is important over this full range of scales. The shortest spatial and temporal scales contain the microstructure variability associated with vertical turbulent mixing. At intermediate scales of tens of kilometers and weeks to months, mesoscale variability is important. At longer periods and larger spatial scales, annual and short-term climate variations (e.g., El Niño) are important. The largest spatial scales and longest periods contain the signals of global change related to atmospheric greenhouse gases and glacial variations.

The multiscale temporal and spatial characteristics of physical oceanographic data demand a large portfolio of statistical analysis techniques to distinguish a signal of interest from measurement noise and the "noise" of unwanted other signals also included in the data. It would be misleading to suggest that physical oceanographers are floundering for need of help from statisticians. Faced with the large volumes of oceanographic data that have accumulated over the past century, physical oceanographers have already acquired an unusually high degree of sophistication in the development and application of statistical analysis techniques. Indeed, with the exception of the atmospheric sciences, which are faced with similarly large volumes of observational data, physical oceanographers are probably more familiar with statistics and the limitations imposed by real (noisy and inadequately sampled) data than are scientists in other disciplines.

At the same time, it would be presumptuous to assume that the statistical techniques presently used in physical oceanographic research are all that are needed. There is undoubtedly a strong need for new and innovative techniques that would yield greater insight into the processes of physical oceanographic variability.

3. BACKGROUND OF THE REPORT

In recognition of the opportunity and need for development and application of statistical techniques in oceanography, the Mathematical Sciences Division of the Office of Naval Research (ONR) initiated a program to foster collaboration between oceanographers and statisticians. The first step of this program was a two-day ONR-sponsored workshop convened in the spring of 1990 for both mathematical scientists and oceanographers. The outcome of the workshop was a new ONR Accelerated Research Initiative (ARI) called Random Fields for Oceanographic Modeling. This ARI provided three years of funding for several collaborative groups of oceanographers and statisticians.

The second step taken by ONR to encourage collaboration between the two groups was a request in May 1991 for a report from the NRC surveying basic statistical research issues motivated by oceanographic applications. The S&PO report reproduced in this volume is the product of that effort. The statement of task from ONR and the history of selection of the panel that wrote the report are described in this section.

3.1 Statement of Task

The charter for the panel was released on August 6, 1991, by the NRC Committee on Applied and Theoretical Statistics under the Board on Mathematical Sciences:

> The Panel of Statistics and Oceanography will produce a report broadly surveying those cross-over areas of greatest potential between statistics and oceanography and recommend research opportunities that should be explored which could lead to the most beneficial advances between these two disciplines.

The text accompanying this Statement of Task further specified that the report was to be approximately 40 pages. It was to be written by an interdisciplinary panel of oceanographers and statisticians at a level accessible to researchers in both fields for use by investigators seeking guidance in appropriate topics for ONR grants in statistics. The writing was to be based on the experiences of the committee members, with input solicited from other experts, as needed. Upon completion, the report was to be subjected to the standard NRC review procedure and 200 copies of the final report were to be delivered to ONR by November 30, 1992.

3.2 Selection of Panel Members

Panel selection adhered to the usual NRC policies. It was decided at the outset that the panel should be co-chaired by an oceanographer and a statistician. Selection of the statistician co-chairperson and four additional statistician panel members proceeded smoothly. Most of these panel members had some previous exposure to oceanographic research through past or present collaborations with oceanographers. Selection of oceanography panel members initially also proceeded smoothly. Two of the oceanography PI's on the ONR Random Fields for Oceanographic Modeling ARI agreed to serve on the panel. A senior-level oceanography co-chairperson and two additional oceanographers also agreed to serve on the panel.

Panel membership was given full approval by the NRC in January 1992, ten months before the final report was due to be delivered to ONR. However, less than a month before the first panel meeting in April 1992, the oceanography co-chairperson abruptly resigned for personal reasons not related to this project. The oceanography membership of the panel was therefore reduced to four, with no co-chair. Efforts began immediately to find a replacement co-chairperson. These efforts had not succeeded by the time of the first panel meeting.

By May 1992, attempts to find an oceanography co-chairperson has still been unsuccessful. It was becoming clear that most of the work of the panel would be completed before a replacement oceanography co-chairperson could be found. As I had effectively been serving in that capacity by default, I agreed to co-chair the panel, although it was my opinion that the panel would benefit from the leadership and experience of a more senior-level oceanographer than myself.

In June 1992, a fifth oceanographer was added to the panel. The oceanography membership of the panel was therefore not complete until midway between the two panel meetings.

Further complicating oceanography representation on the panel, one of the five oceanography panel members was unable to attend the panel meetings or to contribute to the writing of the report, for unfortunate and unavoidable medical reasons. The oceanography representation on the panel therefore effectively consisted of only four panel members, all of whom are physical oceanographers. The breadth of physical oceanographic research, to say nothing of the field of oceanography as a whole, was not uniformly represented by this group. This is reflected in the limited scope of the final report.

4. THE PROCESS OF WRITING THE REPORT

The panel met only twice. The first meeting was held in Washington, D.C., on April 26–27, 1992. For reasons discussed in Section 3.2, only three oceanography panel members were present at the meeting. Prior to this meeting, a list of potential topics that might be included in the report had been provided by ONR. Additional topics were submitted by each of the panel members. The objectives of the first meeting were to refine the list of topics, draft a detailed outline of the report, and assign responsibilities for the writing of each topic to be addressed by the report.

Early discussions at the first meeting focused on the scope of the report. Oceanographic subdisciplines other than physical oceanography were represented on the panel only in the form of past interdisciplinary collaborations of the individual panel members. Lacking any direct representation from these other subdisciplines, it was agreed that the scope of the panel report should be restricted to physical oceanography. This decision was not intended to imply that the other subdisciplines are any less in need of statistical techniques. Indeed, important scientific problems requiring sophisticated statistical analysis techniques can be identified in every other subdiscipline. An outstanding example is the question of what roles the chemistry and biology of the ocean play in moderating the global greenhouse effect of increasing atmospheric carbon dioxide.

The outcome of the first meeting was a distillation of the large number of suggested research problems into a manageable list of seven broadly categorized topics, which later became the chapter headings of the report. The meeting was adjourned with assignments to provide written material within two months.

Following the first meeting, individual panel members wrote text based on personal viewpoints and their own research experiences. In addition, about 10 experts from outside of the panel generously provided written material for the report. All of the contributions were compiled and condensed into a single document during July 1992. Some attempt was made to edit the various contributions to a consistent style, but keeping to the project timetable constrained this effort. A first draft of the report was distributed to panel members in early August for review and comments.

The second meeting of the panel was held in San Diego on August 17–18, 1992. The objectives of this meeting were to discuss the draft report and make modifications as necessary. In addition, the contents of the introductory and concluding chapters were outlined, and responsibilities for writing these chapters were assigned.

Despite considerable efforts by the panel and the NRC staff officer in charge of the project (John Tucker), it was not possible to meet the November 30, 1992 deadline specified in the Statement of Work. This was primarily because of the time lost owing to the resignation of the original oceanography cochairperson and the incomplete oceanography representation on the panel as discussed in Section 3.2. A time extension of six months was granted by ONR.

A final draft of the S&PO report was ready for outside review in mid-December 1992. However, the report was not sent out by the NRC for external review until late January 1993 because of the time required to obtain NRC approval of a revised list of reviewers recommended by the Ocean Studies Board. Comments from four reviewers (two statisticians, one oceanographer and one geophysicist) were received by the panel in early March 1993. After making appropriate changes in response to these comments and upon final approval by the NRC, the report was sent to the printers in late May 1993.

5. THE REPORT

The S&PO report begins with a tutorial overview of physical oceanography, including the equations of motion and conservation that describe geophysical fluid dynamics. Some of the jargon of physical oceanography is introduced and oceanographic usage of the terms "model," "data" and "noise" (which the panel discovered differs from statistical usage of these terms) is clarified. The body of the report surveys seven broad topics in need of statistical analysis techniques. The concluding chapter summarizes suggestions offered by the S&PO panel to foster successful collaborations between statisticians and oceanographers. These suggestions were compiled from discussions that took place between panel members during preparation of the report and out of previous cross-disciplinary research experiences of the panel members.

Probably the most important suggestion made by the panel is that statisticians and oceanographers should work closely together at the same physical location for significant periods of time. This echoes the argument by Hoadley and Kettenring (1990) and others that deep immersion in the subject matter, in order for statisticians to understand fully the scientific issues, is vital to successful collaborations. Working in isolation on data provided by oceanographers is likely to be counterproductive and frustrating to all parties involved.

When preparing the report, the panel acknowledged numerous omissions and incomplete treatments of topics in the report. Subsequently, other omissions and inadequacies have become apparent. Furthermore, even though considerable progress has already been made in all of the topics addressed by the report, there is very little discussion of statistical methods presently used by physical oceanographers, or of the directions of present efforts within the physical oceanographic community toward developing new statistical techniques. There are also no specific examples of statistical analyses.

It was not possible to include any of these valuable enhancements in the report because of the project time constraint and report length limitation. Even without this desirable additional material, the final report (which was completed just in time to meet the extended target completion data) exceeded the requested 40-page guideline by 50%.

Notwithstanding its weaknesses, the panel feels that the report succeeds in achieving the intended objective in the Statement of Work, as presented in Section 3.1. It is hoped that by touching on a broad range of topics, the report will spark interest among statisticians to pursue one or more of the topics in greater depth through close collaborations with physical oceanographers. It can be anticipated that a deeper understanding of oceanographic needs and statistical contributions will develop as a result of such collaborations.

One final point that should be clarified is that the report was not written with the intent of being published in a scientific journal. As originally conceived, the S&PO report was to be widely distributed to the statistics and oceanography communities as an NRC document. However, because of a longstanding print limitation clause in the ONR contract that supports NRC projects such as the writing of this report, it became apparent near the end of the project that the number of copies of the final report that could be printed was far fewer than had originally been envisioned. The publication of the report in its entirety in this journal provides a mechanism for broadening the distribution of the report. Moreover, the overviews of physical oceanography in Section 2 and Chelton (1994) and the discussion papers included in this volume following the report greatly extend the scope of the efforts by ONR and the S&PO panel to increase awareness of the research opportunities in oceanography and to encourage communication and collaboration between statisticians and oceanographers. The S&PO panel is grateful to the individuals who contributed these discussion papers.

6. CONCLUDING REMARKS

Because of space limitation, little information is included in the S&PO report about the scientific problems studied by oceanographers or about the characteristics of observational data. A brief overview of these aspects of physical oceanographic research is presented here in Section 2. A more extensive review from the historical perspective of the technological advancements that have shaped the directions of physical oceanographic research is given by Chelton (1994). Overviews such as these cannot do justice to all of physical oceanography, but they hopefully at least provide useful perspectives for statisticians with little or no previous exposure to physical oceanographic research.

I close this overview by drawing attention to a somewhat delicate issue that statisticians should take into consideration when pursuing collaborative research with physical oceanographers. The need for close and extended collaboration in order for statisticians to conduct analyses with full understanding of the scientific issues was noted in Section 5. There is an even more pragmatic reason that statisticians should work closely with physical oceanographers. Data acquisition is a long and difficult process that begins with a written scientific proposal to collect the data and investigate a specific scientific hypothesis. The proposal is peer reviewed for its scientific content. Recovery of oceanographic data is always a risky business because of the multitude of possible failure points. Successful funding is dependent on the past observational successes of the investigator, as well as on the scientific results obtained from previous studies by the investigator. In the present funding climate, successful funding often requires one or more resubmissions of the proposal.

Once a proposal is funded, a great deal of effort is required to obtain the data. Including transit time, a month of ship time is typically necessary to deploy oceanographic instrumentation. This is preceded by many months of instrument preparation and calibration, sometimes requiring development of new or modified technology. Laboratory space on research ships is allocated much more generously than sleeping quarters. Consequently, manpower on board a ship is limited and 16-hour workdays are common. After deployment, instruments are often left unattended for long periods of time and recovered or refurbished and redeployed on subsequent research cruises. The raw measurements recorded on the data tapes then require considerable data processing effort, including quality-control editing and processing to derive higher-order data sets. Scientific analyses of the data cannot be initiated until all of these phases of data collection and processing are completed.

Because of the time-consuming and expensive effort required to obtain the data before even beginning any analysis, the proprietary nature of oceanographic data sets is understandable. The ultimate expectation of the funding agencies is publications summarizing the scientific conclusions drawn from analyses of the data; data reports are not sufficient. Until the first scientific papers are published, there is a natural reluctance to share the data. Eventually, the data become public domain and are accessible by everyone. It is unrealistic to expect a generous sharing of hard-earned data before the late stages of the project. For this reason, close collaborations and involvement of statisticians in the data processing and scientific issues are likely to be much more successful than simply requesting the data to be analyzed in isolation.

APPENDIX: THE DEMOGRAPHICS OF PHYSICAL OCEANOGRAPHERS

At about the same time that the S&PO report was being finalized, a comprehensive description of the demographics of oceanographers within the United States over the past two decades was published by the Ocean Studies Board (OSB) of the NRC as part of an assessment of scientific opportunities in oceanography (NRC, 1992). The OSB summary covers all subdisciplines of oceanography; an attempt is made here to extract the demographics of physical oceanographers from the 50 pages of tables, bar graphs and text contained in Chapter 4 of the OSB report.

Over the past two decades, the relative proportion of the total number of Ph.D.-level scientists in oceanography who consider themselves physical oceanographers has remained nearly constant at slightly less than 20%. More than 80% of all physical oceanographers are employed by academic institutions or by the federal government. The number of physical oceanographers in the academic/federal sectors increased from about 110/15 in 1970 to about 185/95 in 1980 and about 275/125 in 1990.

In the federal sector, most physical oceanographers are employed at one of the following National Oceanic and Atmospheric Administration (NOAA), U.S. Navy, National Aeronautics and Space Administration (NASA) or National Science Foundation (NSF) government laboratories:

- Atlantic Oceanographic and Meteorological Laboratory, NOAA (Miami, Florida);
- Geophysical Fluid Dynamics Laboratory, NOAA (Princeton, New Jersey);
- Goddard Space Flight Center, NASA (Greenbelt, Maryland);
- Jet Propulsion Laboratory, NASA (Pasadena, California);
- National Center for Atmospheric Research, NSF (Boulder, Colorado);
- Naval Oceanographic Center, U.S. Navy (Stennis, Mississippi);
- Naval Research Laboratory, U.S. Navy (Stennis, Mississippi);
- Pacific Marine Environmental Laboratory, NOAA (Seattle, Washington).

Physical oceanographers are also distributed in small numbers at the NOAA National Marine Fisheries Service facilities and at other federal laboratories around the country. The NOAA, Navy and NASA laboratories are all funded directly by the respective agencies. Changes in these budgets over the past decade have not been clearly documented.

The total number of academic institutions employing oceanographers is about 50. The majority of physical oceanographers in the academic sector are employed by one of the 10 largest oceanographic institutions that have formed a nonprofit corporation [the Joint Oceanographic Institutions, Inc. (JOI)] to facilitate communication between the institutions and coordinate the use of their collective resources. The JOI institutions are the following:

- College of Geosciences and Maritime Studies, Texas A&M University (College Station, Texas);
- College of Ocean and Fisheries Sciences, University of Washington (Seattle, Washington);
- College of Oceanic and Atmospheric Sciences, Oregon State University (Corvallis, Oregon);
- Graduate School of Oceanography, University of Rhode Island (Narragansett, Rhode Island);
- Institute for Geophysics, University of Texas (Austin, Texas);
- Lamont-Doherty Geological Observatory, Columbia University (Palisades, New York);
- Rosenstiel School of Marine and Atmospheric Sciences, University of Miami (Miami, Florida);
- School of Ocean and Earth Science and Technology, University of Hawaii (Honolulu, Hawaii);
- Scripps Institution of Oceanography, University of California (San Diego, California);
- Woods Hole Oceanographic Institution (Woods Hole, Massachusetts).

Other institutions with sizeable physical oceanography faculty include the following:

- College of Marine Studies, University of Delaware (Lewes, Delaware);
- Florida State University (Tallahassee, Florida);
- Naval Postgraduate School (Monterey, California);
- Old Dominion University (Norfolk, Virginia);
- Institute of Marine Science, University of Alaska (Fairbanks, Alaska).

The work of oceanographers at academic institutions, as well as the sources of their salary support, differ significantly from those of faculty members in many other academic disciplines. Only about 10% of academic oceanographers consider teaching to be their primary work. In part, this is because there is generally little emphasis on undergraduate education in oceanography; most institutions offer only graduate degrees. Basic research has been the primary work of a relatively constant 40% of academic oceanographers over the past two decades. The level of institutional ("hard-money") support for physical oceanographers in the academic sector averages to about half-time. The remaining "soft-money" portion of their salaries plus support for research assistants, technicians and graduate students is obtained from research grants and contracts.

The primary sources of research funding for academic physical oceanographers are the NSF and ONR. Collectively, the JOI institutions receive nearly half of the total NSF and ONR budgets for oceanography (all subdisciplines). The 1992 NSF budget for physical oceanography was about $31 million (not including ship support), which represents an increase of approximately 50% over the previous decade in constant 1982 dollars. More than half of this increase occurred in 1986 as a result of the NSF initiatives for TOGA and pre-WOCE activities (see Section 2.7). The 1992 ONR budget for physical oceanographic research was about $40 million, which represents an increase of about 10% over the previous decade in constant 1982 dollars.

The combined NSF and ONR budget (corrected for inflation) for physical oceanography grew by about 25% between 1982 and 1992. In this regard, physical oceanography has fared better than the other subdisciplines of oceanography. Nonetheless, this increase in funding has been far outfaced by the approximate 50% increase in the number of academic physical oceanographers over the same time period. The greater competition for federal funds and the fact that the costs of conducting research have increased faster than inflation have made it progressively more difficult for physical oceanographers to obtain research funding.

As has always been the case, federally funded research is shaped by national political objectives. In the past, this has been very beneficial to physical oceanography. The major technological developments described in Section 2 were largely supported by the ONR because of the Navy's interest in anti-submarine warfare. As in other fields of science, the politics of federal funding in recent years is changing the focus of much of physical oceanographic research. The end of the Cold War has reduced the emphasis on national security and is changing the character of defense-related research. The bureaucratic emphasis on the relevance to national goals and on research deliverables (e.g., Brown, 1993; NRC, 1993) has further constrained the topics of research. It is highly unlikely that the rapid developments in physical oceanographic research over the past three decades summarized in Section 2 could have occurred in the present funding climate. There is a serious concern whether sufficient resources can be made available to exploit fully future technological developments, as has always been possible in the past.

The field of physical oceanography is thus in a state of transition, adjusting to the political, social and financial climate of the 1990's. The general trend has been a shift of funding away from individual research toward large, cooperative projects involving multiple investigators, often including the international physical oceanographic community. Most of these projects address large and complex interdisciplinary questions such as the role of the ocean in global climate discussed in Section 2.7. While not uniformly supportive of these changes, physical oceanographers are adapting by maximizing the scientific content of research constrained to address questions of societal importance.

Fortunately for physical oceanographers, there are many scientifically interesting and challenging problems that are also important to society. Perhaps most pressing is an improved understanding of the many manifestations of the role of the ocean in global climate variability on a wide range of time scales. A related issue is the role of air–sea interaction in shorter-time-scale weather variability. The effects of physical oceanographic variability on the biological food chain and marine fisheries are also important. On a more local scale, the dispersal of pollutants in nearshore waters and increased beach erosion expected to accompany global sea level rise are issues of growing concern. It is safe to say that physical oceanography will survive the present transitional period, but the emphasis of research a few years from now may be quite different than it has been in the past.

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