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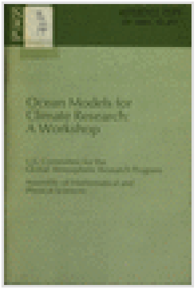

Ocean Models for Climate Research: A Workshop (1980)

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U.S. Committee for the Global Atmospheric Research Program
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Preface

This report is concerned with models of oceanic circulation and processes related to climate modeling. It first presents a selected review of ocean modeling currently in progress, including studies being carried out (1) directly for climate research and (2) for other purposes but pertinent to the climate problem. It then discusses directions for research progress, attempting to define important and feasible problems of a scientific and technical nature and to identify the resources and arrangements necessary for their accomplishment. It is a report concentrating solely and in detail on this subject matter. The intent is to provide some guidance both for scientists engaged in or intending to initiate research in this area and also for individuals generally responsible for planning and directing climate research programs.

In the past several years increased interest in climate has resulted in a sharpening of the climate research problem. The oceans have emerged as a component of the climate system regarded as crucially important and requiring a special research effort. The recently established World Climate Research Program has explicitly recognized this point. The task is complicated because of the large number of oceanic processes and phenomena reasonably considered to be of importance to climate dynamics. Moreover, empirical and dynamical knowledge of these oceanic phenomena is lacking. In particular, numerical ocean modeling, an essential component of contemporary ocean science and of climate modeling, is a relatively novel and small field, which is evolving rapidly.

The workshop, held in Boulder, Colorado, October 31-November 2, 1979, was thus considered both necessary and timely. This report was prepared from notes of the workshop first drafted by William Simmons and then circulated to the participants. During this process, both the Bibliography and the table on Ocean Modeling Problems for Climate Studies were developed. The intent of the workshop was to provide a balanced and comprehensive overview; the vast scope of the subject makes, however, some influence of the individual participants inevitable. We thank William R. Holland and his colleagues at the National

Center for Atmospheric Research for excellent local arrangements, and we are especially grateful to William Simmons as rapporteur and consultant and John S. Perry and Thomas H. R. O'Neill of the U.S. Committee for GARP for their expert assistance throughout this project.

Allan R. Robinson, *Chairman*
Workshop Organizing Committee

Contents

1
Summary of Recommendations

During the course of the workshop, the various types of ocean modeling relevant to climate research were reviewed and evaluated in terms of their inherent strengths and limitations. Recommendations were made regarding (a) activities that show the most promise for solving problems of immediate interest and (b) new areas of endeavor that are required in ocean modeling for climate research. The projected needs for observational data and computer resources were also discussed, and recommendations were made. The recommendations appear in Chapter 4. For the reader's convenience, these recommendations are summarized below in four groups: modeling, data, resources and support, and organization. Some recommendations appear in more than one group. Within each group, recommendations are listed in the order in which they appear in the text; no effort was made to assign priorities. Page references indicate where the full recommendation may be found.

1.1 MODELING

- Primitive equation model studies are relevant to aspects of the climate problem and should be continued in those areas of ocean modeling where there are no reliable alternate models (page 15).
- Efforts should be made to develop a correct nonadiabatic quasi-geostrophic model capable of modeling ocean thermodynamic processes with greater efficiency and economy than do primitive equation models (page 16).
- Systematic intercomparisons among primitive-equation and quasi-geostrophic models with clearly delineated parametric variations, higher resolutions, and stronger nonlinearities than heretofore should be conducted to explore potential dynamical differences in regions of strong currents, severe topography, or intense thermodynamic processes, with a view toward better understanding of these model systems (page 16).

- The feasibility of intermediate models with increased efficiency over primitive equation models should be explored, particularly for use in equatorial dynamical problems (page 16).
- Quasi-geostrophic model studies should be continued and extended to take advantage of their efficiency and economy; models should be extended to allow for greater vertical resolution, i.e., six or more layers as in primitive-equation models (page 17).
- Efforts should be continued to understand and to refine our ability to parameterize effectively subeddy-scale processes important to mixing, diffusion, and dissipation in eddy-resolving models (page 18).
- Efforts should be increased to understand the physical basis of valid parameterizations of the eddy scale and to improve the parameterizations utilized in coarse-grid models, taking into account the expected variation of the processes in different dynamical regions and geographical locations. Liaison should be maintained between ocean modelers and workers in related turbulence theory (page 19).
- Process-oriented observational and modeling studies of the ocean's planetary boundary layer should be continued, with the goal of accurately modeling the heat exchange between ocean and atmosphere, heat redistribution within the ocean, and the prediction of sea-surface temperature over the annual cycle (page 19).
- Efforts should be supported to embed dynamically correct mixed layers into regional and general circulation models and to test GCM's with detailed mixed-layer models against field data in a variety of settings important to climate dynamics, i.e., upwelling regions, regions of deep wintertime convection at high latitudes, and regions of high mesoscale activity (page 19).
- To strengthen ties between mixed-layer modelers and GCM modelers, cooperative efforts within the climate modeling community should be encouraged and supported to foster communication between mixed-layer and GCM dynamicists and between ocean mixed-layer dynamicists and their atmospheric counterparts in planetary boundary-layer dynamics (page 20).
- A table of ocean modeling problems important to climate research separated by time scale should be developed on the basis of Table 1 of this report and should be updated from time to time (page 21).

1.2 DATA COLLECTION

While it was neither fitting nor prudent to design measurement programs at a modeling workshop, certain parameters were singled out as being of primary importance to ocean models and suggestions regarding their measurement were made.

• Process-oriented observational and modeling studies of the ocean's planetary boundary layer should be continued, with the goal of accurately modeling the heat exchange between ocean and atmosphere, heat redistribution within the ocean, and the prediction of sea-surface temperature over the annual cycle (page 19).

• A greatly increased number of surface wind measurements should be sought using a variety of methods for direct wind measurements near the equator and via the surface pressure field at higher latitudes supplemented with occasional direct measurements (page 25).

• Heat and mass flux parameters should be measured routinely at least as often as surface winds, and in some zones more often. These measurements should have the same priority as surface wind observations. Development of new, more accurate and reliable measurement techniques should be encouraged (page 25).

• High-accuracy, high-resolution temperature and salinity data should be collected from a number of special dynamical regions particularly relevant to climate research: equatorial regions, western boundary currents, and nearby intense eddy fields; high-latitude regions of wintertime convection, upwelling regions; and ring regions (page 26).

• Accurate time series of current measurements should be made using a variety of currently available direct techniques in regions identified as important to climate research. New instruments and techniques, including satellite observations, showing promise of the requisite measurement accuracies, should be pursued and developed (page 26).

• Process-oriented observational programs focused on such problems as exchange between surface and deep waters, surface and intermediate waters during winter, mechanisms of water mass formation, and Ekman pumping in the subtropical gyres should be conducted (page 27).

1.3 RESOURCES AND SUPPORT

• Heat and mass flux parameters should be measured routinely at least as often as surface winds, and in some zones more often. These measurements should have the same priority as surface wind observations. Development of new, more accurate and reliable measurement techniques should be encouraged (page 25).

• Estimates of projected needs (Table 3) prepared by the workshop participants should be communicated to the Ocean Sciences Board's Computing Resources and Facilities for Ocean Circulation Modelling Committee for refinement and as an input to their deliberations, together with the serious concerns of the workshop participants about projected shortfalls in resources (page 29).

Note: Almost all items in categories 1.1 and 1.2 would also fit into category 1.3.

1.4 ORGANIZATION

• To strengthen ties between mixed-layer modelers and GCM modelers, cooperative efforts within the climate-modeling community should be encouraged and supported to foster communication between mixed-layer and GCM dynamicists and between ocean mixed-layer dynamicists and their atmospheric counterparts in planetary boundary-layer dynamics (page 20).

• A modelers advisory group or some other mechanism should be established to provide input broadly from the modeling community to the compilation of historic data relevant to ocean modeling and to maintain liaison with archivists and data analysts performing this work (page 21).

• Communication and liaison should be maintained with workers in radioactive waste disposal to explore mutual or overlapping modeling requirements and data needs (page 27).

• The USC-GARP Climate Dynamics Panel should consider the establishment of two working groups of theoreticians, modelers, and experimentalists to improve the interaction between theory and modeling and the design of field programs and data-management schemes. The groups should deal with the following areas, respectively:

1. Shorter time-scale climate variability studies, including tropical dynamics,
2. Climate sensitivity studies on long time scales, including geochemistry, water mass formation, and the global heat balance (page 27).

• Ocean climate modeling workshops should be organized about every two years to permit discussion and assessment of research progress and to map out directions for new inquiry (page 30).

2
Introduction

The Workshop on Ocean Models for Climate Research was organized by the U.S. Committee for the Global Atmospheric Research Program at the suggestion of its Climate Dynamics Panel. It was conceived as a direct and logical outgrowth of the Joint Organizing Committee/Scientific Committee on Oceanic Research (JOC/SCOR) Joint Study Conference on General Circulation Models of the Ocean and Their Relation to Climate, Helsinki, May 23-27, 1977. That Study Conference was organized (a) to review the status of both dynamical modeling of the ocean and climate and coupled ocean-atmospheric systems and (b) to stimulate communication between ocean and atmospheric modelers, with a view toward improving the modeling of climate and its variability. The fields were reviewed comprehensively, allowing participants from the various specialized disciplines to gain a general appreciation for the variety of problems involved in ocean modeling and climate modeling and to provide a common basis from which to proceed. The review papers were published in preliminary form by the World Meteorological Organization, Geneva, Switzerland, in November 1977, and in final form in a special edition of the *Dynamics of Oceans and Atmospheres* (Volume 3, Nos. 2-4, 1979), edited by A. R. Robinson and D. J. Baker, Jr. The latter contains most of the conference papers and discussion summaries and provides substantial background documentation for the present report.

The Helsinki Conference of 1977 did not deal primarily with ocean models focused specifically on climate problems. The Workshop on Ocean Models for Climate Research was therefore organized to fill the gap. Its objectives were the following:

1. To review what is being done in ocean modeling relevant to climate-dynamics research, including both models specifically intended for this purpose and other large-scale and regional models;
2. To discuss research plans and to recommend what could or should be done with present models and feasible model developments in order to advance important climate research objectives.

Participants were asked:

1. To present current modeling results in selected representative areas with emphasis on their implications for climate research (Chapter 3 and Appendix B);
2. To point out intended or immediately possible extensions for climate research purposes (Chapters 3 and 4);
3. To note deficiencies in, or new developments required for, models in climate-dynamics research (Chapter 4).

The intention of the workshop was to provide a forum for focused interactions among ocean modelers in order to review the status of climate models and to communicate, formulate, criticize, and stimulate new plans for ocean-modeling research aimed at climate problems. This report of the workshop includes a brief summary of the status of ocean modeling for climate research as well as recommendations on issues and directions for future climate research.

3
Ocean Models for Climate Research

3.1 INTRODUCTION

The set of ocean models now in use for studies of interests to climate research is exceedingly diverse, including coarse-grid, fine-grid, primitive-equation, quasi-geostrophic, quasi-analytic, non-Newtonian, global, regional, deep-water, mixed-layer, wind-driven, thermally driven, coupled, and interactive models. This diversity derives in part from the difficulty of the task, i.e., the wealth of oceanic processes that now must be considered as potentially important and the overall status of physical oceanography. Modeling the composite ocean/climate problem on global space scales and climatic time scales with the resolution required to resolve explicitly and simultaneously all the oceanic phenomena of interest would be forbiddingly expensive, if indeed available computer resources could be found to handle the job. A variety of more feasible modeling approaches must therefore be explored. Even if funds and facilities were available, ocean modelers—like their atmospheric counterparts—would likely disagree seriously on how to treat a number of fundamental modeling questions, e.g., how to parameterize convective, frictional, or mixing processes in the surface waters or thermocline and whether to resolve eddies. Moreover, were these questions to be successfully resolved, one would still need to identify and to collect the large-scale long-term data sets needed to calibrate, initialize, verify, and test the model.

In the interest of understanding and economy and in order to relate to available or potential data sets, modelers have dissected their problem into more manageable pieces. These have been approached using the tools thought to be most appropriate to the task. As a result, a diverse set of more manageably sized and somewhat specialized models have evolved, although even some of these require considerable computing facilities (see Table 3 in Chapter 4).

3.2 GENERAL CIRCULATION MODELS

Any serious atmospheric climate model of duration longer than a season will have to be coupled to an ocean general circulation model (GCM) of at least the upper water, which simulates correctly the large-scale air–sea interaction over the time scales of interest. Ocean GCM's of varying completeness and complexity exist and can produce mean flows that resemble in some respects the observed general circulation of the upper ocean (Robinson and Baker, 1979). Some of the coarser-grid models constructed for long time-scale studies require fairly large lateral viscosity values to eliminate subgrid-scale noise (Pond and Bryan, 1976). Correspondingly, major features predicted by them are weaker and more diffuse than observations suggest, but the general distribution of velocity and temperature features is fairly good (Holland, 1979). Salinity has been modeled only rarely, but it is necessary to do so to study the global heat balance and hydrologic cycle (Bryan, 1979). The coarse-resolution GCM's are the basis of the oceanic components currently used for large-scale coupled air–sea interaction studies as mentioned below.

Ocean modeling is, however, severely complicated by the existence in much of the world's oceans of mesoscale eddies with time and space scales, respectively, of weeks to months and tens to hundreds of kilometers (The MODE Group, 1978). Although called "mesoscale" by many oceanographers, dynamically these nearly geostrophic turbulent eddies may be thought of as the oceanographic counterparts of the atmospheric synoptic scale; however, the analogy must be drawn with caution as there are important differences. First, ocean eddies are not perturbations on an energetic mean flow. The greater part by far of oceanic kinetic energy is bound up in the eddy scale, and this scale of motion may play an important role in the poleward transport of heat (Semtner, 1979; Bryden, 1979). Secondly, they are relatively small in horizontal extent so that ocean climate models, which must have the same overall exterior dimensions as atmospheric GCM's (i.e., global), will require more than 20 times the latitudinal and longitudinal resolution as atmospheric models if the eddies are to be resolved. Because eddies play an active role in the energy budget and are suspected to be important in the heat transport mechanisms, their resolution has been pursued in ocean general circulation studies. Many ocean GCM's are therefore eddy-resolving general circulation models or EGCM's (Robinson *et al.*, 1979). EGCM's can accommodate considerably decreased values of lateral viscosity; therefore sharper, more intensive, and more realistic flow features are obtained.

There are two well-developed types of eddy-resolving ocean models applicable for climate research–process models and general circulation models:

Process models use idealized (rectangular) midocean domains with periodic boundary conditions and concentrate on interactions between physical mechanisms (the β-effect, topography, stratification, nonlinearity) that determine the local statistical properties of the model runs (Rhines, 1975, 1977; Owens, 1979; Bretherton and Haidvogel, 1976; Haidvogel and Held, 1980). These are usually unforced spin-down experiments, and although not directly relevant to climate modeling, they are essential tools in developing reliable eddy-resolving general circulation models and for guidance in parameterization studies (see below).

General circulation models, which are also analyzed mechanistically, are more realistic models of partial or entire ocean basins, usually reminiscent of the North Atlantic (Holland, 1978, 1979; Robinson *et al.*, 1977; Semtner and Mintz, 1977). They are usually driven by steady winds and sometimes thermal forcing and are capable of producing realistic circulations having separating, meandering western boundary currents, cold and warm core rings, spontaneously generated mesoscale eddies with correct geographic intensities, recirculation currents, and quasi-Sverdrup mean return flows in rough overall quantitative agreement with observations. These models have been extended to polar (McWilliams *et al.*, 1978) and equatorial (Semtner and Holland, 1980) regions. Analysis of model eddy fields has produced new insights into the dynamical mechanisms of recirculation gyres, deep currents (Schmitz and Holland, 1980), and pole-ward heat transports near the Gulf Stream front (Semtner, 1979). Consistently correct overall amplitudes and absolutely realistic instantaneous flow patterns are not yet obtainable.

General circulation experiments are usually spun up from rest to or near statistical equilibrium. The near-equilibrium investigations that are considered valid for ocean circulation studies may not be adequate for some climate-related problems. Although elaborate schemes are sometimes used to carry out the spin-up process efficiently, *primitive equation* (PE) models tend to consume relatively large amounts of computer time. Some modelers believe them to be limited in their present scientific usefulness by computer power and resources. Hence, *quasi-geostrophic models* are also used because of their greater economy (Holland and Lin, 1975a; Holland, 1979). Future work with quasi-geostrophic models will be aimed toward understanding the local behavior of energy and vorticity within different regions of large-scale model runs, testing potential vorticity mixing theories, exploring solution characteristics as a function of model parameters, exploring the effects of realistic bottom topography and unsteady (seasonally varying) wind and thermodynamic forcing, and comparing model energetics with real data sets from POLYMODE with regard to frequency content, depth dependence, and geographical variability.

Future *primitive equation* models will be aimed toward thermodynamic and coupled wind/thermal forcing studies, reformulating bottom friction parameterization, extension to realistic multiple-gyre systems (i.e., the entire North Atlantic) with realistic bottom topography, using small-grid-size runs for a simplified global ocean, embedding prognostic surface mixed layers, adding salinity as an independent parameter, introducing sea-ice extent and thickness as prognostic variables, and coupling with existing atmospheric GCM's. Primitive equation models are time consuming, especially when deep ocean thermally forced circulations, which are important for longer-term climate variability, are included. Schemes to improve efficiency have been put forward, e.g., using longer time steps in the deep water than in the upper ocean and coupling the two calculations at regular intervals, much as ocean-atmospheric interactive models are coupled. Still, these models require considerable computer time. It will be recommended below that quasi-geostrophic models directly or modified as possible or necessary be explored in an effort to accomplish these same goals.

The overall data base used to test most models is generally inadequate. Recent large-scale experiments have improved this situation somewhat. For example, the recent POLYMODE data set holds much promise as a dense, long-term data set (Hartline, 1979). However, it is very confined in lateral extent and in time. The FGGE oceanographic data set is also promising, but it is confined to equatorial regions and is quite sparse in other parts of the world (Oceanographic Programme for the FGGE, 1978). Models are therefore often tested by intercomparison one with another or by parameter sensitivity studies within a given model.

Although most GCM's and EGCM's were originally developed for ocean-dynamics studies, they have been adapted to problems in climate research, and, interestingly, new climate-related results have begun to appear. A simple two-layer quasi-geostrophic model without heating has displayed, in a limited parameter range, an unmistakable large-amplitude long-term vacillation in the flow pattern and overall energy level with a characteristic time of about two years or more (Holland and Haidvogel, 1980). This time scale is well removed from linear baroclinic instability scales. Such vacillations are found in many other circumstances including laboratory rotating flows during transitions from laminar to turbulent flow. Moreover, the spectrum of deep ocean variability from moored current-meter observations appears to be red down to the lowest frequencies that can be resolved. Needless to say, the relevance and implications of vacillations to climate are now under intensive study, and there is in progress a search for other long-term model variabilities that might bear on climate dynamics.

Several varieties of *coupled ocean-atmospheric models* have recently begun to appear. A few preliminary models have highly idealized ocean systems coupled in simplified ways to more realistic atmospheric flows. These are most useful in large-scale interaction studies, where, at the present preliminary level of inquiry, small-scale details are of secondary importance. In the simplest case, the ocean is modeled as a thin copper plate that conducts heat only vertically and is important only for thermal driving. Early climate sensitivity studies were conducted with highly parameterized atmospheric models coupled to uniform mixed-layer oceans incapable of poleward heat transports and other important thermodynamic processes (Suarez and Held, 1976; Lemke, 1977). More sophisticated coupled models, some with dynamically active, vertically mixable upper ocean layers, have been developed and are now being refined and intercompared (Haney, 1979a, 1979b; Washington *et al.*, 1980). Manabe *et al.* (1979) have put forward a promising climate sensitivity model that combines large-grid-sized fully detailed atmospheric and ocean models such as those used in global circulation studies (Bryan and Lewis, 1979). These are quite complex and demanding of computer time. The demand is accentuated when the thermohaline circulation, important for long-term variability studies, is modeled.

In an effort to facilitate longer-term integrations, some modelers have developed "lower-order" models, not directly derivable from first principles but based instead on simple but plausible *ad hoc* physics (McWilliams and Gent, 1978; 1979; 1980). These appear to be useful to explore the variety of solution types that obtain as the controlling physical parameters are varied over wide ranges. Still other models have interacting atmospheric and ocean components in a seasonal sequence and endeavor to include all the important climate elements, i.e., winds, precipitation, components of the surface energy balance, and sea ice. These show promise and are under active development.

It was the understanding of the workshop participants that atmospheric models for climate research are continually being revised to improve their ability to respond reliably to longer-term variabilities associated with thermodynamic and topographic forcing and other effects important to climate. In addition, recent research (Schneider and Thompson, 1980) has shown that the transient response of the coupled atmosphere-ocean-cryosphere system to a transient perturbation could well be of different character than the equilibrium response calculated either with an atmosphere GCM or a coupled ocean-atmosphere GCM. Truncated spectral models and models with implicit timestepping appear to offer promise for long-term integrations with manageable computing requirements (Held and Suarez, 1978).

3.3 REGIONAL MODELS

The problems of modeling the circulation of the world's oceans for climate dynamics and other research purposes are large in scope and include geographical heterogeneity in geometry and dynamics. It is not surprising therefore that various regional models have been developed as part of the scientific evolution toward a fully global climate model. Certain ocean regions have been selected for model studies because of a belief in their particularly important role in climate dynamics, e.g., polar seas, equatorial seas, western boundary currents, and upwelling regions. Those discussed at the workshop are summarized below without regard to order, since it is too soon to assign priorities to such selected regions over others in terms of their ultimate importance to the climate problem.

A considerable amount of modeling effort related to observations and experiments has been devoted to the world's tropical oceans in a number of cooperative scientific programs (i.e., GATE, INDEX, FGGE, EPOCS), and other programs are currently being planned (PEQUOD, SEQUAL) (Philander, 1979). The amplitude of the ocean poleward transport of heat is thought to be a maximum near the boundaries of the tropics (Oort and Vonder Haar, 1976), and numerical simulations of the tropical atmosphere (prescribed change experiments) have shown particular sensitivity to anomalous ocean forcing. The equatorial oceans have a highly variable and highly structured ocean current system and are subject to strong annual forcing signals, particularly in the Atlantic and Indian Oceans. In the Pacific, interannual variability dominates. The relatively short tropical baroclinic response time suggests that useful statistics for model verification could be collected in a relatively short time, making ocean monitoring and modeling appear particularly attractive in some equatorial regions. (Long-term data sets useful for climate modeling research are so rare that climate monitoring anywhere in the world's oceans must be regarded as useful.)

Equatorial models have been especially successful in explaining long-term variabilities in island and deep-sea tide-gauge records (Wyrtki, 1975, 1979; Wunsch and Gill, 1976), in providing a plausible mechanism for the annual change in the thermocline depth in the Atlantic Ocean (Katz *et al.*, 1977; Moore *et al.*, 1978; O'Brien *et al.*, 1978; Philander, 1979), in explaining the generation of Indian Ocean currents (Cox, 1976, 1979; Knox, 1976; Cane, 1980), and in producing a mechanism for the interannual El Niño phenomenon (Hurlburt *et al.*, 1976; McCreary, 1976). However, recent observations have suggested that the equatorial current system is much deeper, more highly structured, and probably more complicated than had been thought (Luyten and Swallow, 1976; Eriksen, 1980). New modeling results also suggest a complex structure of mean currents and waves near the equator. Internal instabilities and trapping of eddy energy in the equatorial waveguide appear to be possible (Semtner and Holland, 1980).

Because of the existence of the various equatorial observational programs noted above, equatorial dynamicists are rather well organized. Moreover, climate-research goals provide considerable motivation for these programs. Unfortunately, no specialists in equatorial dynamics were able to attend the workshop. Written comments were, however, provided for discussion and inclusion herein.

High-resolution models have enjoyed considerable success in accurately modeling details of actual flows in limited regions with good data coverage. Loop currents in the Gulf of Mexico have been modeled from their inception in the Yucatan Straits to their ultimate dissipation in the northwest corner of the Gulf and have been shown to be synoptic or mesoscale variabilities rather than seasonal phenomena as had been thought (Hurlburt and Thompson, 1980).

The Antarctic Circumpolar Current and its instability-associated variabilities have been studied with some success in initial experiments (McWilliams *et al.*, 1978). Gulf Stream models are central elements of the midlatitude EGCM's discussed in the preceding section. Models of western boundary currents other than the Gulf Stream, including those of the southern hemisphere, are under development.

An open-ocean regional model for a limited midlatitude, midocean area has been constructed for use in hindcasting and idealized dynamical studies involving the POLYMODE data (Haidvogel *et al.*, 1980; Robinson and Haidvogel, 1980). This model is generally applicable to eddy-intensive midlatitude regions and should contribute to eddy heat transport and parameterization studies, both by simulations and in a forecast or "nowcast" mode of operation in conjunction with a real-time observational network (Bengtsson, 1975). Near-surface eddy heat transports (Voorhis *et al.*, 1976) will be studied by coupling a quasi-geostrophic model to a near-surface-layer model (Stevenson, 1980).

A regional modeling study (Haidvogel, 1980) is under way in the shelf/slope region west of the Gulf Stream to determine the interaction between coastal and deep-sea circulations and to clarify the nature of the physical/dynamical connection between these two regions. The study is focusing on (a) heat and momentum transports across the continental shelf brake associated with westward-propagating mesoscale rings and eddies and (b) along shore sea-level variations suggested by the large-scale deep-ocean circulation. The dynamic and thermodynamic coupling between the continental shelf and deep-ocean circulations is thought to be of climatic significance for at least two reasons. First, the shelf is a considerable heat reservoir with large seasonal temperature fluctuations and is active in gyre heat recirculation through Gulf Stream warm core rings. Secondly, flow along the continental margin can be thought of as a boundary-layer component of the exterior ocean circulation. A refined description of the closure of the open-ocean flow by the shelf/slope system will contribute to an understanding of how to model appropriately the wind- and eddy-driven general circulation.

3.4 MIXED-LAYER MODELS

Mixed-layer models (Kraus, 1977) and GCM's with simple parameterizations of the mixed layer have had considerable success in simulating large-scale thermal anomalies in the upper ocean (Haney *et al.*, 1978). Such a primitive equation model was spun up to equilibrium with seasonally varying climatological data and then forced with observed data for a given season. It produced anomaly patterns similar to those observed in the North Pacific Ocean. The model runs used NORPAX data, including TRANSPAC temperature structures down to 400 m, to initialize and verify the simulations. The results demonstrated the importance of horizontal advection and, for the first time, the importance of vertical mixing of heat for the development of the observed temperature anomalies. These studies are important for climate because the positions and intensities of such anomalies in the Pacific, especially in the equatorial Pacific, have been correlated with climate fluctuations over the North American continent (Davis, 1978). This model is now under refinement to include, among other things, an embedded mixed-layer model.

Other high-resolution mixed-layer models are adapted to selected high-data-density regions and used for detailed short-term simulations of large-amplitude features such as current fronts (resolution from 300 km downward). Available expendable bathythermograph (XBT) data are used together with climatology to initialize the model, which then computes geostrophic and Ekman currents, which in turn advect and deform the temperature field. The temperature field can be reinitialized every three days using whatever data may have been collected in the interim, and the model is thus used operationally for predictions (Clancy and Martin, 1979;1980). This model is currently undergoing tests for longer-term predictability skill and for sensitivity to deep flows and variations in climatology.

3.5 QUASI-ANALYTICAL MODELS

Quasi-analytical techniques have also shown much promise (Veronis, 1973; 1976; 1978). Typically, analysis is used to derive a dynamical system governing the behavior of a flow of interest, which is then solved by numerical methods. A promising mechanism for wind curl intensification by sea-surface temperature variations has been uncovered using this technique (Beringer *et al.*, 1979; Bye and Veronis, 1980). Other phenomena of interest to climate research have also been uncovered using this approach, including long-term oscillations in a sea-ice–air–saltwater system and the discovery of topographically induced recirculation gyres (Veronis, 1980).

4

Issues and Directions for Ocean-Modeling Climate Research

After presentations of current research interests and directions in climate modeling, the workshop participants were divided into six subgroups to address the six specific topics regarded as most relevant to future work in climate modeling.

4.1 MODELS

This subgroup set out to discuss (a) primitive-equation and quasi-geostrophic models; (b) "intermediate models," which are neither wholly primitive-equation nor quasi-geostrophic models but intermediate between these two; and (c) "lower-order models," which are based on an intuitive physics not derivable from first principles but analogous in at least some aspects to the fundamental laws (e.g., Burger's equation in turbulence theory) and to assess the relevance of each to climate research objectives.

Multilayered primitive-equation models, although they consume large amounts of computer time, were judged to be essential for the following:

1. Frontal dynamics in which the Rossby number approaches or exceeds unity (such as the climatically important Gulf Stream region where the sea-to-air heat flux reaches an absolute global maximum during winter).
2. Studies of the vertical diffusion of horizontal momentum. This topic is central to ocean physics, and quasi-geostrophic formulations appear to be inherently incapable of rendering physically consistent formulations of the mixing problem, although bulk Rayleigh laws may be adequate for some purposes.
3. Equatorial dynamics in general. Here we simply know of no other less-complicated models in which the problems can be correctly formulated. Such a model may be possible, but it has not yet been formulated. A search to discover such a model is recommended as a useful area for future study.

RECOMMENDATION. Primitive-equation model studies are relevant to aspects of the climate problem and should be continued in those areas of ocean modeling where there are no reliable alternative models.

Quasi-geostrophic models, which are far more economical and efficient than primitive-equation models, are applicable in some ocean subregions but at present do not include changes in water mass properties due to thermodynamic processes. Therefore, it was felt that a new class of reliable high-resolution nonadiabatic quasi-geostrophic models capable of modeling high-amplitude oceanic thermodynamic processes correctly is needed. Preliminary models exist, and research in this area should be carried out in the early 1980's.

RECOMMENDATION. Efforts should be made to develop a correct nonadiabatic quasi-geostrophic model capable of modeling ocean thermodynamic processes with greater efficiency and economy than do primitive-equation models.

Models that may be put forward should be tested by *systematic intercomparisons* with modern primitive-equation models. Indeed, the workshop participants felt that carefully designed systematic intercomparisons of existing quasi-geostrophic and primitive-equation models would be a useful contribution toward furthering our understanding of both model systems. Some intercomparisons have been carried out but only for cases where strong nonlinearities were prevented by the horizontal grid scale and where more than one parameter was varied. Zero-order agreement between the two types of models was found.

RECOMMENDATION. Systematic intercomparisons among primitive-equation and quasi-geostrophic models with clearly delineated parametric variations, higher resolutions, and stronger nonlinearities than heretofore should be conducted to explore potential dynamical differences in regions of strong currents, severe topography, or intense thermodynamic processes, with a view toward better understanding of these model systems.

Intermediate models for climate studies may indeed be appropriate. The nonadiabatic quasi-geostrophic models and equatorial models recommended above could fall into this category. Implicit methods, familiar in global meteorological modeling (Mesinger and Arakawa, 1976), may also be promising in narrowing the efficiency gap between primitive-equation and quasi-geostrophic models. Other examples are difficult to formulate at present, but it was felt that thorough primitive-equation/quasi-geostrophic model intercomparisons might inspire new ideas in this area.

RECOMMENDATION. The feasibility of intermediate models with increased efficiency over primitive-equation models should be explored, particularly for use in equatorial dynamical problems.

The efficiency of *quasi-geostrophic models* is most noteworthy in mechanistic studies of eddy dynamics, where a large number of runs must be analyzed and intercompared. Although originally identified in primitive-equation studies, it was primarily through such quasi-geostrophic model studies that significant sources and generation mechanisms for eddies were defined in a generalizable way, that eddy-induced recirculation gyres were shown to cause downstream enhancement of the Gulf Stream transport, and that deep mean model flows were found and shown to be by-products of the eddy field.

RECOMMENDATION. Quasi-geostrophic model studies should be continued, to take advantage of their efficiency and economy; models should be extended to allow for greater vertical resolution, i.e., six or more layers as in primitive-equation models.

The workshop participants adopted a neutral position toward *low-order models*, neither encouraging nor discouraging them. Models to date were thought to have provided some valuable insights, strengthening the opinion that best progress will likely be achieved through an interactive mixture of model studies.

4.2 PARAMETERIZATIONS

All models have subgrid-scale processes that must be parameterized, i.e., the mesoscale eddies in GCM's and frictional dissipation in both GCM's and EGCM's. How best to formulate these parameterizations has been a central and actively controversial topic of turbulence research for decades and remains so in atmospheric and oceanic modeling to the present. Consequently, clear-cut recommendations on how best to proceed could not be formulated, but guidelines and opinions were given for (a) high-resolution models resolving scales including those of the mesoscale eddies and for (b) those resolving scales greater than eddies.

4.2.1 Eddy-Resolving Models

Here, subgrid scale or "frictional" dissipation must be modeled. Most eddy modelers now use Ekmanlike bottom friction as the dominant momentum-dissipating process. Eddy models are usually heat insulated everywhere except at the surface. If bottom friction does in fact dominate, can the form of the horizontal friction matter? Modelers currently do not only use classical or "low-order" schemes such as aerodynamical drag and Newtonian ∇^2 friction. Modern higher-order schemes, which effectively terminate the enstrophy cascade without overdamping the model as a whole, include biharmonic ∇^4 friction, the Shapiro (1971) filter, and other forms such as Tokioka's (1978), which is based on a quasi-geostrophic turbulence closure theory. It was felt that in the parameter ranges being investigated at present, distinctions between the higher-order forms were perhaps not crucial in the interior of the ocean, and it was recognized that tests to prove or disprove this conjecture would require extremely high resolution and therefore costly experiments.

However, physical dissipation mechanisms near boundaries, that required mix of high- and low-order forms, and the influence of boundary conditions were discussed as important and unsolved problems. For example, the question of slip versus no-slip lateral boundary conditions, and the associated lateral friction form, remains a difficult one. Western boundary current separation, and thereby entire gyre circulations, may be intimately tied to the nature of the boundary conditions. Vorticity input varies markedly for slip versus no-slip conditions.

If bottom friction does not dominate, then lateral friction, local or global, is likely to be the controlling factor. But what are the physical processes? The workshop participants were unable to resolve this question but observed that the global enstrophy cascade probably terminates in horizontal frictional processes. The possibility of geographical variability, i.e., bottom processes dominating in some areas and lateral processes in others, was recognized.

Other bottom interaction processes such as flow over finite amplitude topography of varying scales may not yet be adequately parameterized, even for their qualitative effects. Over smooth bottoms, new processes, such as the shearing off of lenses of the bottom boundary layer (Armi and D'Asaro, 1980), may require new parameterization. Data collected in conjunction with research in nuclear-waste disposal in or on the seabed may be useful for future models on these topics.

RECOMMENDATION. Efforts should be continued to understand and to refine our ability to parameterize effectively subeddy-scale processes important to mixing, diffusion, and dissipation in eddy-resolving models.

4.2.2 Noneddy-Resolving Models

Here the discussion focused on the parameterization of the mesoscale eddies for the coarser-resolution large-scale models. Specific questions are: (a) How useful is an eddy coefficient model in which the diffusivity is a function of the mean currents and the eddy kinetic-energy levels (McWilliams, 1977; Harrison, 1978)? (b) Does its utility vary from slowly varying regions, to intense jet regions, to topographically rough (scattering) regions? (c) How sensitive are model results to a diffusivity formulation of this general form? (The workshop participants recognized that closure schemes other than first-order eddy-coefficient closures, which allow for nonlocal effects, are in common use in meteorological models. However, their application to ocean models was not discussed.)

Even in the limit of quasi-geostrophic turbulence, parameterization of eddy statistical properties such as heat flux in terms of mean flow quantities is surprisingly difficult (Haidvogel and Held, 1980). Schemes for estimating mixing coefficients with K_V/K_H given by the slopes of isopycnal surfaces have been put forward. However, experience gained from observations and models in MODE/POLYMODE suggests that such a formulation would be practical only in relatively quiescent regions, which were thought to be of lower priority for climate research than nonhomogeneous high-energy jetlike flow regions. However, this problem is difficult and exists full blown in both atmospheric and oceanic model formulations.

RECOMMENDATION. Efforts should be increased to understand the physical basis of valid parameterizations of the eddy scale and to improve the parameterizations utilized in coarse-grid models, taking into account the expected variation of the processes in different dynamical regions and geographical locations. Liaison should be maintained between ocean modelers and workers in related turbulence theory.

4.3 SURFACE PROCESSES

Accurate simulation of the flux of heat and momentum in the surface mixed layer of the ocean is essential for coupled ocean–atmosphere climate models. Three-dimensional models that include detailed specification of the upper-ocean planetary layer are required. Although a great deal of progress has been made with one-dimensional models of the upper ocean, no synthesis has yet been made that includes all the elements of the most detailed one-dimensional model in a full three-dimensional model that includes horizontal advection in a realistic way. Field studies of the oceanic planetary layer have not been sufficiently detailed to pinpoint the exact turbulent processes that are most important. For example, are Langmuir cells the main source of mixing near the surface? Is kinetic energy carried down from the wave zone, or is local shear instability more important for entrainment of denser fluid at the base of the mixed layer? However, progress is being made. For example, it has been shown that the vertical mixing of mean momentum within the mixed layer is likely to be of central importance to the vertical mixing of heat.

RECOMMENDATION. Process-oriented observational and modeling studies of the ocean's planetary boundary layer should be continued, with the goal of accurately modeling the heat exchange between ocean and atmosphere, heat redistribution within the ocean, and the prediction of sea-surface temperature over the annual cycle.

It is also important that the most important elements of the mixed-layer models be included in GCM's designed for climate research. This work has already begun.

RECOMMENDATION. Efforts should be supported to embed dynamically correct mixed layers into regional and general circulation models, and to test GCM's with detailed mixed-layer models against field data in a variety of settings important to climate dynamics, i.e., upwelling regions, regions of deep wintertime convection at high latitudes, and regions of high mesoscale activity.

It is important that workers in the area of mixed-layer dynamics communicate frequently before publication of research results. The workshop participants commend the newsletter *Ocean Modelling*, distributed by the Department of Applied Mathematics and Theoretical Physics, University of Cambridge, for providing a most useful forum for mixed-layer modelers.

RECOMMENDATION. To strengthen ties between mixed-layer modelers and GCM modelers, cooperative efforts within the climate modeling community should be encouraged and supported to foster communication between mixed-layer and GCM dynamicists and between ocean mixed-layer dynamicists and their atmospheric counterparts in planetary boundary-layer dynamics.

4.4 MULTIPLE TIME SCALES

Energetically important ocean phenomena relevant to climate studies occur on a myriad of time and space scales, e.g., dissipation, microstructure, waves, meandering, fronts, mesoscale eddies, seasonal, annual and interannual responses, vacillations, and fluctuations in gyrewide circulations. These interdependent phenomena are modeled in different ways by different modelers, depending on objectives and facilities. The workshop participants undertook (a) to extract from the class of all ocean model problems those specifically relevant to climate processes; (b) to arrange them according to time scale; and (c) to list and contrast the methods by which the various problems are being attacked, including both their strengths and their limitations (for example, to contrast coarse- versus fine-grid models of North Atlantic circulation).

The purposes of the exercise are fourfold:

1. To set out in clear fashion the problems that must be addressed and to estimate the level of effort now being devoted to them.
2. To search for omissions in the overall modeling strategy.
3. To stimulate increased interest in climate modeling.
4. To stimulate new ideas on how these subproblems may interact or be interconnected. For example, it was conjectured that a numerical analog to the analytical method known as "two-timing" may well arise as a computer-efficient solution to multiple-scale interaction problems. Work along these lines has already been initiated (Marchuk, 1974).

The workshop participants suggested that the results of this exercise be presented in the form of a table and developed a preliminary version (Table 1). Recognizing that a complete table can only evolve as a result of inputs from a broad group of modelers, the workshop participants produced this first approximation using its collective resources, but with the intention that it should grow and be updated from time to time as additional inputs are received from the community. In general, entries should primarily represent things that can now be done with existing resources but may also reflect research that will become possible with improving computing resources and techniques.

RECOMMENDATION. A table of ocean modeling problems important to climate research separated by time scale should be developed on the basis of Table 1 of this report and should be updated from time to time.

4.5 DATA SETS FOR OCEAN MODELING

4.5.1 Historic Data

Most historic data relevant to ocean climate modeling either have been or are now in the process of being assembled for use in climate models by data-analysis specialists in government agencies, research institutions, and the private sector. Ocean modelers welcome these contributions and would like to assist in the design of final products so as to assure their maximum utility for modeling purposes. Specifically, if historic data are to be used for the development and verification of ocean models, it is of utmost importance that probable errors (instrumental errors and sampling errors, for example) be estimated and assigned so that uncertainties in the basic data may be assessed.

RECOMMENDATION. A modelers' advisory group or some other mechanism should be established to provide input broadly from the modeling community to the compilation of historic data relevant to ocean modeling and to maintain liaison with archivists and data analysts performing this work.

4.5.2 Climate Variability Data

For future data sets for climate research, we distinguish between the needs for *climate variability* studies (one- to ten-year time scales) and *climate sensitivity* studies (ten years and longer).

For climate variability data, one has in mind synoptic, survey-like measurement programs on a basin scale, of one or two years' duration, with fully adequate resolution of the seasonal signal. Examples of relevant parameters are surface meteorological variables, heat and salt content of the upper ocean, and currents as possible (see Table 2).

Satellites hold promise for future measurements of this kind. However, data are needed now, and for them modelers must rely almost wholly on more conventional measurements that are not remotely sensed. Ideally, one would like *simultaneous* measurements of atmospheric and oceanic parameters relevant to working models, so that causal relationships may be sought to explain data correlations. This is particularly true in tropical regions where cause and effect appear to be more directly relatable. In this sense the FGGE IIIb data set should

TABLE 1 Ocean Modeling Problems for Climate Studies

< 1 Year	1–10 Years	10^1–10^2 Years	10^2–10^3 Years	> 10^3 Years
SURFACE CIRCULATION AND MONTHLY-SEASONAL SST VARIATION • 1-D mixed-layer models • Mixed-layer model embedded in a coarse-grid global GCM • Mixed-layer models imbedded in GCM that has mesoscale resolution • Coarse-resolution-idealized or real ocean model • Upwelling, coastal and equatorial • Transient-wave-response models	INTERMEDIATE WATER FORMATION, WINTERTIME COOLING • Improved QG models with active thermodynamic and water mass formation • Mixed-layer model embedded in a coarse-grid global GCM	BOTTOMWATER FORMATION • Geochemical tracers	THERMOCLINE STRUCTURE BOTTOMWATER FORMATION • Coarse resolution idealized or real ocean model • Mesoscale resolution (QG models with active thermodynamics for the thermocline problem)	ICE-AGE DYNAMICS (Ocean–Atmosphere Ice Dynamics)
MIDLATITUDE HIGH-RESOLUTION REGIONAL OPEN-OCEAN AND PROCESS MODELS • Isolated eddy evolution (i.e., rings)	MIDLATITUDE HIGH-RESOLUTION REGIONAL OPEN-OCEAN AND PROCESS MODELS			
	MIDLATITUDE GYRE AND ACC CIRCULATION VARIABILITY	SOUTHERN OCEAN CIRCULATION (mesoscale QG experiments to explore the interaction of the ACC with midlatitude regions)		

POLEWARD HEAT-TRANSPORT MECHANISMS including QG eddy-resolving models with active thermodynamics to study the role of eddies in transporting heat	POLEWARD HEAT-TRANSPORT MECHANISMS including QG eddy-resolving models with active thermodynamics to study the role of eddies in transporting heat	POLEWARD HEAT-TRANSPORT VARIABILITY	
EQUATORIAL THERMOCLINE • PE models ranging from one vertical mode to multilevel models	EQUILIBRIUM EQUATORIAL DYNAMICS • Mesoscale resolution, PE models for small idealized domains	GULF STREAM AND EQUATORIAL EQUILIBRIUM EDDY/WAVE DYNAMICS • Mesoscale ($\Delta s \leq 40$ km) resolution GCM (idealized ocean basin model) • Mesoscale with "real" ocean basins (e.g., North Atlantic)	
	INTERANNUAL VARIABILITY OF TROPICAL OCEAN–ATMOSPHERE SYSTEM • Coupled model of intermediate complexity • Low-order coupled models • El Niño phenomena (Pacific)		
	COUPLED AIR–SEA VARIABILITY	TRANSIENT RESPONSES • Transient response of a coupled ocean–atmosphere model to changes in atmospheric radiation balance • Penetration of global-scale temperature anomalies and geochemical tracers from the surface into deeper waters	RESPONSE TO CO_2 LOADING IN THE ATMOSPHERE

TABLE 2 Examples of Types of Data Sets Needed for Model Development and Verification

Data Type	Source	Function
Surface wind stresses, air temperatures and humidities	Marine deck	Upper boundary condition
Sea-surface temperature	Marine deck	Upper boundary condition
Sea-surface salinity	NODC hydrographic files	Upper boundary condition
Bottom topography	Scripps/Rand 1° X 1°	Lower boundary condition
Vertical profiles of temperature and salinity	NODC hydrographic file	Initialization and verification
Geochemical tracer data (tritium, bomb-produced ^{14}C	GEOSECS	Boundary conditions, mixing, verification
Ocean currents	Original investigators, NODC files	Initialization and verification

be the best possible combined ocean–atmospheric parameter data set ever acquired in the tropics. The FGGE global wind field alone, with annual-cycle trends removed, should comprise the best possible forcing function for global ocean models. Ocean modelers anxiously await these data.

Climate-variability data should be focused on upper layers, where response on the one- to ten-year time scale will be more pronounced. Parameters related to processes that exchange heat, tracers, and momentum vertically, particularly in the vicinity of the equator but also at higher latitudes, are of prime interest since these must be correctly represented in ocean models for climate variability. Data on midocean mesoscale eddies, particularly in the vicinity of major current systems (i.e., Gulf Stream, Kuroshio), and vertical fine-structure phenomena near the equator are also of especially high priority. Data from low-latitude coastal regions where large-scale thermal anomalies occur are also needed.

It is neither fitting nor prudent to endeavor to design measurement programs at a modeling workshop, but certain parameters were singled out as being of primary importance to ocean models. They are as follows:

1. *Surface Winds.* Over most of the ocean, surface wind data are crucial because of the importance of local forcing mechanisms. In some regions, sampling

may be on a coarser grid than other ocean-surface parameters. For example, Gulf Stream fronts are not caused by wind events of a similar spatial scale. Winds in equatorial regions are identified as being especially important, as are southern hemisphere winds. This is done with full knowledge of the remoteness of these regions and the difficulty of mounting ship-of-opportunity programs there.

RECOMMENDATION. A greatly increased number of surface wind measurements should be sought using a variety of methods for direct wind measurements near the equator and via the surface pressure field at higher latitudes supplemented with occasional direct measurements. Techniques should include:

(a) Ships of opportunity, including U.S. commercial and Navy vessels, as well as fullest possible support from the international fleet.

(b) Satellite scatterometer measurements with sufficient ground truth to resolve directional ambiguities.

(c) Drifting buoys with surface pressure and, if possible, direct wind-measuring capabilities.

(d) Cloud motions, if they can be made reliable.

(e) Technological work to devise new, preferably fully automated, unmanned instruments for measuring surface wind speed and direction should be carried out.

2. *Heat and Mass Fluxes.* Here marine deck observations may be sufficient. However, because sea-surface temperatures can have relatively small spatial scales, resolutions greater than those for wind data will be required in some regions. New automated techniques to improve accuracy, eliminate human error, and enhance coverage should be devised.

RECOMMENDATION. Heat and mass flux parameters should be measured routinely at least as often as surface winds, and in some zones more often. These measurements should have the same priority as surface wind observations. Development of new, more accurate, and reliable measurement techniques should be encouraged.

3. *Ocean Temperature and Salinity Structure.* These measurements are important not only for the computation of current shears but are also indicators of both vertical and horizontal dynamical processes relevant to climate. High-accuracy, high-resolution temperature and salinity data are needed from the following regions:

(a) *Equatorial*, where large-scale variabilities cause significant atmospheric changes in higher latitudes and where open ocean as well as coastal upwelling play such an important role. Liaison should be maintained with experimental programs such as PEQUOD and SEQUAL.

(b) *Western boundary currents and their extensions*, which are prime agents in the poleward heat flux process and are involved in direct and intense heat exchange with the atmosphere.

(c) *Intense eddy fields near western boundary currents*, since these appear to play an important role in the poleward heat-flux process.

(d) *High-latitude regions of wintertime convection* thought to be source regions for intermediate and deep waters.

(e) *Upwelling regions* in general, where surface waters are formed and where anomalous temperatures lead to intense atmospheric heat exchanges.

(f) *Ring regions*, since these recirculate considerable quantities of heat in the poleward direction. The working group did not attempt in the short time available to assign priorities to the above regions. It simply regarded them as being especially relevant now. The climate-dynamics program in oceanography is of broad scope, and several years of research will be required in order to identify with certainty the most critical regions for special process studies.

RECOMMENDATION. High-accuracy, high-resolution temperature and salinity data should be collected from a number of special dynamical regions particularly relevant to climate research: equatorial regions, western boundary currents, and nearby intense eddy fields; high-latitude regions of wintertime convection; upwelling regions; and ring regions. In the absence of instrumentation or ship time for high-accuracy, high-resolution temperature–salinity measurements, expendable instrumentation is recommended.

4. *Currents.* Direct measurements of ocean currents are important both to estimate absolute velocities and to gain longer-term statistics. These are crucial for model verification. Future capabilities for large-scale and mesoscale current determinations through satellite geodesy and other new techniques such as pop-up floats and acoustic tomography should be pursued if sufficient accuracy can be achieved. Every effort should be made to press forward with these endeavors. In the meantime, however, long time series of current measurements are required for model development and verification. These should be supported through deep-water current-meter moorings, arrays of SOFAR floats, appropriately drogued surface drifters with real-time reporting capability (the latter two being also well suited to diffusion studies), ship-of-opportunity Doppler shift profilers, and cyclesondes adapted for time series measurements. New instrumentation suitable for such measurements would be heartily welcomed. Regional priorities are similar to those for hydrographic data.

RECOMMENDATION. Accurate time series of current measurements should be made using a variety of currently available direct techniques in regions identified as important to climate research. New instruments and techniques, including satellite observations, showing promise of the requisite measurement accuracies, should be pursued and developed.

4.5.3 Climate Sensitivity Data

In climate sensitivity models, one is concerned with processes that lead to exchange between surface and deep waters. For this purpose, detailed data sets on tracers such as tritium and bomb-produced carbon-14 are particularly valuable, provided the data are accompanied by good error estimates (instrumental and sampling errors).

Process-oriented experiments are required to generate focused data sets on deep-water formation in high latitudes and intermediate-water formation in mid-latitudes during winter. Field measurements to estimate the downward pumping of surface water in subtropical gyres by Ekman currents are desirable. The reverse process by which upwelled water is warmed to form surface water along the equator and continental coastlines also requires attention. Process experiments such as these provide opportunities for physical oceanographers and geochemists to combine forces on problems of mutual interest.

RECOMMENDATION. Process-oriented observational programs focused on such problems as exchange between surface and deep waters, surface and intermediate waters during winter, mechanisms of water mass formation, and Ekman pumping in the subtropical gyres should be conducted.

Because of the global and long-term aspects of radioactive waste disposal, modeling requirements and data needs will overlap. Also, a goal of the modeling community is to provide answers to critical circulation/mixing questions put forward by researchers in waste disposal.

RECOMMENDATION. Communication and liaison should be maintained with workers in radioactive-waste disposal to explore mutual or overlapping modeling requirements and data needs.

The workshop participants perceived clear needs for a continuing mechanism to establish and disseminate informed modeling opinion in climate studies through regular meetings, to provide for interaction between modelers/theoreticians and field experimentalists and to make recommendations concerning funding of and support for data sets important for ocean-modeling research.

RECOMMENDATION. The USC-GARP Climate Dynamics Panel should consider the establishment of two working groups of theoreticians, modelers, and experimentalists to improve the interaction between theory and modeling and the design of field programs and data-management schemes. The groups should deal with the following areas, respectively:

1. Shorter time-scale climate variability studies, including tropical dynamics;
2. Climate sensitivity studies on long time scales, including geochemistry, water-mass formation, and the global heat balance.

4.6 RESOURCE AND SUPPORT REQUIREMENTS

Participants at the workshop expressed their concern over projected computer resources. Modelers are now being pressed by climate objectives to construct

TABLE 3 Computing Estimates for Ocean-Climate Modeling in the Early to Mid 1980's

A. Computing requirements for "typical jobs" in Cray (or equivalent machine) hours (= 1/6 of 7600 h)		
1. Moderate-resolution (4500 km)^2 three-layer quasi-geostrophic box model with Δs = 25 km at Δt = 3 h:		
10-yr integration requires		10 Cray h
10-yr integration with irregular geometry requires		20 Cray h
2. High-resolution (1000 km)^2 three-layer quasi-geostrophic box model with Δs = 5 km and Δt = 1/2 h:		
5 yr ↔		33 Cray h
3. Small equatorial primitive equation model (14 levels; 3000 × 2000, $\Delta x = 1/2°$, $\Delta y = 1/4°$, Δt = 1/2 h)		
5 yr ↔		25 Cray h
4. World ocean primitive equation model with five levels	$\Delta s = 1°$: 20 yr ↔	100 Cray h
	$\Delta s = 0.5°$: 20 yr ↔	1000 Cray h
5. Small high-resolution channel with	Quasi-geostrophic model = 20 yr ↔	75 Cray h
	Primitive equation model = 20 yr ↔	1000 Cray h
6. One-mode equatorial basin model: (4500 km)^2 with Δs = 60 km		
10 yr ↔		1/3 Cray h
7. Two-level atmospheric model ($\Delta y = 3°$ + three zonal waves) with implicit time stepping		
10 yr ↔		2/3 Cray h
B. Estimated future needs		
1. 20 investigators running 5 cases/yr of 10-h Cray/case: 1000 h		
2. 5 investigators running 5 cases/yr of 100-h Cray/case: 2500 h		
3. 2 investigators running 1 case/yr of 1000-h Cray/case: 2000 h		
$\frac{5500 \text{ Cray h}}{360 \text{ days/yr}}$ = 15 Cray h/day, essentially full usage		

larger models and to intensify ancillary computations (intercomparisons and parameter studies, for example) with present models. It appears certain that unless preventive measures are taken now ocean modeling will soon suffer a computer-time famine. Very rough estimates of computer usage per year in the next few years (Table 3) suggest that for climate-related research ocean modelers will require the equivalent of a dedicated Cray-1 computer, i.e., ocean-modeling requirements will be roughly equal to present atmospheric climate requirements.

Many suggestions were made on how to correct the situation, e.g.,

1. Increase facilities for oceanographic use at already established computing centers.
2. Establish a new ocean-modeling center with a Cray-equivalent computer on a par with the present NCAR facility.
3. Establish or augment a central Cray-equivalent computer facility with moderately well-equipped regional subcenters.
4. Opt for slower machines of the minicomputer class with dedicated, fully equipped regional subcenters.

It was regarded as outside the scope of the workshop to formulate specific procedural recommendations. The workshop participants were advised that a panel of the NRC Ocean Sciences Board has been charged with examining all aspects of future computer resources for oceanography and that SCOR's Committee on Climate Change and the Oceans has also forecast inadequate computer support for ocean climate modeling on an international basis. The workshop participants therefore requested their chairman to refer the issue with urgency to the Ocean Sciences Board's Computing Resources and Facilities for Ocean Circulation Modelling Committee.

RECOMMENDATION. Estimates of projected needs (Table 3) prepared by the workshop participants should be communicated to the Ocean Sciences Board's Computing Resources and Facilities for Ocean Circulation Modelling Committee for refinement and as an input to their deliberations, together with the serious concerns of the participants at the workshop about projected shortfalls in resources.

5
Future Meetings

Because ocean modeling for climate research encompasses ocean modeling broadly, because it is now in a state of rapid evolution, and because effective modeling depends on results from work in other disciplines that are also developing rapidly, it is important that ocean modelers meet regularly at workshops such as this to discuss and assess climate-oriented results and to stimulate new directions for inquiry. Meetings should be spaced to allow time for substantial advances in modeling results, but not so far apart that lack of communication inhibits progress. At present, it is estimated that one ocean climate modelers' workshop every two years will be sufficient, the next one to be scheduled around the third quarter of 1981.

RECOMMENDATION. Ocean climate-modeling workshops should be organized about every two years to permit discussion and assessment of research progress and to map out directions for new inquiry.

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Appendix A: Participants

Allan R. Robinson, Harvard University, *Chairman*
Francis P. Bretherton, National Center for Atmospheric Research
Kirk Bryan, National Oceanic and Atmospheric Administration
Peter R. Gent, National Center for Atmospheric Research
Dale B. Haidvogel, Woods Hole Oceanographic Institution
Young-June Han, Oregon State University
Robert L. Haney, U.S. Naval Postgraduate School
William R. Holland, National Center for Atmospheric Research
James C. McWilliams, National Center for Atmospheric Research
Yale Mintz, National Aeronautics and Space Administration
Steven A. Piacsek, Naval Ocean Research and Development Activity
Albert J. Semtner, Jr., National Center for Atmospheric Research
George Veronis, Yale University
Warren Washington, National Center for Atmospheric Research

Agency Liaison Representatives
Edward S. Epstein, National Oceanic and Atmospheric Administration
Rex Fleming, National Oceanic and Atmospheric Administration
Elbert W. Friday, Department of Defense

Written Comments were Provided to the Workshop by
Mark A. Cane, Massachusetts Institute of Technology
George Philander, National Oceanic and Atmospheric Administration

Staff
John S. Perry, National Research Council, *Executive Scientist*
William Simmons, *Consultant and Rapporteur*

Appendix B: Workshop on Ocean Models for Climate Research

Agenda

Wednesday, October 31, 1979

1. Opening of the Meeting
   a. Purposes and objectives of the meeting (Robinson, Holland, Perry)
   b. Schedule of work
   c. Approval of agenda
   d. Local arrangements (Holland)
2. Scientific Presentations
   a. Ocean General Circulation Models
      (1) A review of eddy resolving GMC's (Holland)
      (2) Long time scale vacillations in eddy resolving GCM's (Haidvogel)

Coffee

      (3) Proposed ocean modeling for climate research (Mintz)
      (4) A global ocean model with imbedded mixed layer (Gates/Han)

Lunch

   b. Regional Ocean Circulation Models
      (1) Eddy shedding in the Gulf of Mexico (Piascek)
      (2) Equatorial modeling (McWilliams)
   c. Mixed-Layer Models
      (1) A global mixed-layer model (Piascek)
      (2) Upper-ocean thermal variability: prescribed change experiments with OGCM's (Haney)
   d. Coupled Ocean–Atmosphere Models
      (1) An NCAR coupled atmosphere/ocean/sea-ice model (Washington)
      (2) A coupled model of intermediate complexity (Semtner)

Coffee

   e. Quasi-analytic Models
      (1) A localized heat transfer/wind-stress feedback system (Veronis)
   f. Other Topics
      (1) A lower-order coupled model for the equatorial circulations (Gent)

Thursday, November 1, 1979

   g. Other Scientific Topics
      (1) Development of a dynamical forecast model with eddy/mixed-layer interactions (Robinson)
      (2) Data sets for modeling (Bryan)

(3) Continental slope/deep-ocean coupling: Observations and future research (Haidvogel)

Coffee

3. Scientific Discussion
   a. A general scientific discussion of the work and proposals presented at the workshop
   b. Identification of topics for further consideration
   c. Summary of the status of ocean modeling for climate dynamics

Lunch

3. Continuation of Scientific Discussion
4. Discussion of Recommendations
   a. Model developments required for climate research—World Climate Program and longer-term phenomena
   b. Potential collaborations
   c. Gaps in present research activities
   d. Support facilities: computers, data sets, observational programs
   e. Review of structure, content and production of the report of the meeting

Friday, November 2, 1979

5. Recommendations of the Meeting
   a. Principal recommendations of the meeting will be listed, reviewed, and placed in scientific context

Coffee

6. Final Scientific Discussions and Plan for Production/Circulation of the Report of the Workshop

Workshop Adjourned