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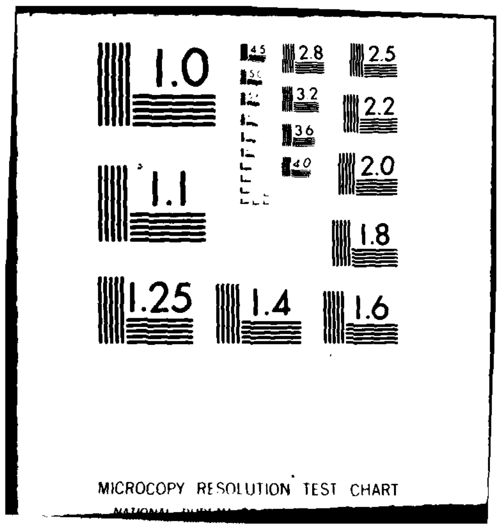
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An Assessment Of Computational Resources Required For Ocean Circulation Modelling

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This report documents the probability of a significant shortage by 1984 in the availability of computer resources for ocean circulation modelling. Computers are the modern tool with which scientists calculate answers to problems in all fields of inquiry. In the natural sciences it is straightforward to pose extensive and complicated calculations that must be done on large-scale computers. Such disciplines as physics, chemistry and meteorology have effectively used each new generation of fast computers to improve understanding of nature, generate hypotheses and make laboratory data meaningful. In particular, meteorologists have gained new understanding of atmospheric dynamics and applied their knowledge to improve weather forecasts. Oceanographers are now proposing to expand their use of high speed computers to increase their physical understanding of the ocean and to apply it to problems, in climate, fishery management, long-range weather prediction and management of ocean resources.

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AN ASSESSMENT OF COMPUTATIONAL RESOURCES REQUIRED FOR OCEAN CIRCULATION MODELLING

Ad Hoc Committee on

Computing Resources and Facilities
for Ocean Circulation Modelling

Ocean Sciences Board

Commission on Physical Sciences, Mathematics,
and Resources

National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

Ocean science covers a great diversity of environments and requires correspondingly diverse methods of study. The aim of the science, however, is to display the underlying coherence in the processes that drive the physical, chemical and biological systems in the ocean. Achieving this aim requires a knowledge the dynamics of these systems over a wide range of space and time scales from local, short-term episodes to long-term, global changes. These larger conceptual patterns are emerging and will be of great significance not only for our basic understanding but for many applied issues. To develop and test these concepts will require the correct balance between theory and observation, and this in turn demands the most effective deployment of the methods needed for these studies.

In this context, the Ocean Sciences Board has organized studies of certain major resources that are critical for the future progress of our research. These studies examine manpower, computers, remote sensing and research ships. Together, they should provide one basis for the most efficient use of our financial resources. These studies can also be viewed as a framework within which our future scientific programs will develop.

The rapid emergence of geophysical fluid dynamics as a separate theoretical discipline has had a profound effect on the interplay of theory and observation concerning the ocean. The greatly expanding need for large "numerical experiments" complements the increasing capability to obtain denser data sets from the ocean using ships and satellites. Thus Ocean Circulation Modelling is an essential component of progress, not only in oceanography, but for our understanding and management of the earth as a system.

This report sets out the requirements for large computing resources based on the scientific needs for the decade of the 1980's.

John H. Steele, Chairman
Ocean Sciences Board

FOREWORD

This report documents the probability of a significant shortage by 1984 in the availability of computer resources for ocean circulation modelling. Computers are the modern tool with which scientists calculate answers to problems in all fields of inquiry. In the natural sciences it is straightforward to pose extensive and complicated calculations that must be done on large-scale computers. Such disciplines as physics, chemistry and meteorology have effectively used each new generation of fast computers to improve understanding of nature, generate hypotheses and make laboratory data meaningful. In particular, meteorologists have gained new understanding of atmospheric dynamics and applied their knowledge to improve weather forecasts. Oceanographers are now proposing to expand their use of high speed computers to increase their physical understanding of the ocean and to apply it to problems in climate, fishery management, long-range weather prediction and management of ocean resources.

It should be recognized that physical oceanography and meteorology are sister sciences since both deal with a part of the Earth's fluid envelope. Our understanding of these geophysical fluids is undergoing a revolution because of the availability of fast, large computing capability. The natural physical systems have large numbers of degrees of freedom and complicated interactions between different time and space scales. Ocean modelling can advance rapidly in the decade of the 1980's in a fashion corresponding to the pioneering work of meteorologists.

Historically, European and American scientists have been predicting storm surges since the first computers were available following World War II. Each country bordering the North Sea has a team of storm-surge modellers that use computers and the weather forecast to predict tides and storm surges along the coastline. In the United States a small dedicated group of scientists continue to improve models to predict the hurricane storm-surge and its effect on manmade and natural coastal structures.

In the 1960's a few oceanographers in government meteorological laboratories and universities began serious development of large-scale ocean models. The lack of sufficient ocean data to compare with the calculations was a serious problem. Modellers were prone to exaggerate the comparability of their results to the existing data. To some extent the same bias exists today. An example is the tendency to claim success when one has achieved simple comparisons, such as the correct order of magnitude of the transport of western boundary currents.

The International Decade of Ocean Exploration in the 1970's greatly changed theoretical oceanography. Several large multi-investigator projects brought together observationists and applied mathematicians. Examples are CUEA, ISOS, MODE, NORPAX and POLYMODE. These projects collected extensive data in coastal upwelling regions, the Antarctic Circumpolar Current, North Atlantic and the North and Equatorial Pacific. Each data set showed us that our earlier theoretical models were inadequate to explain the observed time and space variability. Each project encouraged the creation of numerical modelling groups to explain the complicated physics of the region under study. In the late 1970's, it was recognized that ocean circulation models were needed to understand climate and provide predictions for naval operations. In order to improve medium range weather forecasts and short term (3-6 months) climate forecasts, the role of the ocean must be understood. This can only be accomplished in a satisfactory manner with large-scale, coupled atmospheric-ocean models. Adequate models of this type do not exist at present. The U.S. Navy has encouraged the enhancement of ocean modelling in order to explore the possibility of an environmental predictive capability for fleet operations.

Many ocean resource management problems may be more clearly understood through the application of selected ocean circulation problems. Examples are ocean dumping, ocean pollution, management of fisheries, search and rescue, marine meteorology, and ship-routing.

The Committee is convinced that there is a class of extensive ocean circulation models that will increase our basic scientific understanding of the ocean and assist in selecting solutions to national problems. In addition, these cannot be done on small computers. *Ocean numerical modelling has recently become an important part of ocean science and plays today an essential role in the advance of the science itself.* This report documents the need for increased computing resources to make such an advance possible.

We wish to acknowledge the support and encouragement of our corresponding members and the data provided by numerous oceanographers in the United States. Also we appreciate the facilities and staff help provided by Harvard University, the University of Texas and the Ocean Sciences Board during our committee meetings. I also thank Ruth Pryor and Pat Teaf for their excellent professional staff assistance and Bert Semtner for his assistance in completing this report.

James J. O'Brien
Chairman

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EXECUTIVE SUMMARY

The ad hoc Ocean Sciences Board Committee on Computing Resources and Facilities for Ocean Circulation Modelling was assigned two tasks in late 1979:

Task 1 -- To identify on the basis of scientific needs the computing activities for the decade of the 1980's for ocean dynamics and circulation modelling and to estimate the resources required.

Task 2 -- To recommend mechanisms for providing the required computing resources identified in Task 1.

The Committee was composed of theoretical physical oceanographers, atmospheric modellers and two experienced computer center managers. Three meetings were held. It was apparent at the first meeting that the members of the committee all recognized the exciting scientific opportunities in understanding ocean circulation that are made available only by the use of numerical models.

First Finding

1. *Ocean numerical modelling has recently became an important part of ocean science and plays today an essential role in the advance of the science itself.*

There are increasing national interests in understanding and utilizing the ocean. The Federal and state Governments need guidance for the management of fisheries and the control of ocean dumping and pollution. The Navy, Coast Guard and commercial interests need advice on ocean variability in such operations as ocean resource management, ship-routing, search and rescue, and naval operations.

Second Finding

2. There are important national programs involving ocean science that require an accelerated development and application of ocean models.

The Committee made their own assessment of the available computing resources in the United States and concluded that additional resources were needed. A survey of U.S. experts supported this conclusion. However, there was one surprise.

Third Finding

3. A survey of the ocean modelling community indicates that planned computer resources will be adequate for the needs of federal laboratories in 1984 in the sub-area of scientific ocean modelling.

On the other hand, the academic portion of the ocean modelling community, defined as university and college researchers including ocean modellers at the National Center for Atmospheric Research, expect to experience a dramatic shortage of available computer resources for the scientific calculations they plan to perform. There are very important scientific problems that are capable of solution that cannot be solved any other way.

Fourth Finding

4. The same survey indicates that the projected computing resources of the academic ocean modelling community will fall short of their projected needs in 1984 by a factor of 2, and will fall short of a scientifically feasible and desirable level of use by a factor of 4.

The Committee supports the idea that our knowledge of the ocean must continue to increase. Since ocean modelling is a vitally important activity in developing new knowledge and understanding, an effort should be mounted to lessen the shortage of computer resources. Specifically:

Fifth Finding

5. *To ensure the advancement of oceanography as a science, there is a requirement for a class 6 computer facility by 1984.*

The Committee was also concerned with the availability of manpower in ocean modelling. An assessment was made of available people and of the rate of growth in this speciality field. We were pleased to discover that:

Sixth Finding

6. *There has been a doubling of Ph.D. ocean modellers in the past 5 years, and there exists now adequate manpower for effective utilization of new computer resources.*

It was determined that these new Ph.D.'s have advanced mathematical and statistical training to appreciate and to use effectively the results of ocean model studies for scientific advancement.

Based on the findings, the Committee was able to summarize its recommendations as follows:

Recommendation 1

1. *In view of the scope and magnitude of the needed computation resources, we recommend that the resources of a class 6 system or equivalent be established for ocean modelling research. It should be a computing resource accessible for use on a scientific merit basis by the entire academic ocean modelling community of the United States. The allocation of the resources should be the responsibility of the oceanographic community.*

Recommendation 2

2. *Whereas adequate resources are not now available or being planned, and in view of the lead time required in their acquisition, we recommend that planning begin without delay to provide the necessary computing resources.*

We do not recommend a specific location for this new computer resource. The facility should be located at an appropriate center that is experienced in large scale computing. Several university sites and national laboratories are obvious candidates.

INTRODUCTION

The search for understanding of nature has always been driven by two motivations. We want to be able to explain our Universe in simple terms. Why does it rain? Why are waves created when the wind blows? Why does high tide occur at different times in different places? We also want to solve economic and social problems. Can we predict when it will rain? Can we direct ships to avoid uncomfortable seas? Can we warn coastal communities of unusually high sea level? Each theoretical answer has practical consequences. The ocean has always fascinated mankind. History documents the centuries of intellectual inquiry through which we have tried to explain our observations of the ocean. The 1980's will be no exception. During the 1970's, the International Decade of Ocean Exploration, the scientific community has had a unique opportunity to obtain vast quantities of data that have raised numerous new questions about the ocean's behavior. We have discovered that the deep ocean is not quiescent. We have learned that, like the atmosphere, the ocean contains "storms", commonly called mesoscale eddies or rings. We have found that seasonal variations in near Equatorial winds create enormous variations in currents and temperatures thousands of kilometers away with time-delays of a few months. We have discovered that charts that show surface currents in one direction are hiding deep strong currents transporting water and its contents in the opposite direction. We have discovered that well-known currents disappear when we look during a certain time of year. The list of new discoveries is almost boundless.

The observation that the deep ocean is not still has an impact on international decisions to dump waste in the ocean and the environmental effects of oceanic industry. The mesoscale eddies raise questions regarding ocean heat transport and its role in determining climate variations. The equatorial low-frequency long-distance teleconnections mean that managers of the Peruvian fisheries need to understand the weather near the Gilbert Islands. The European fisheries in the Gulf of Guinea may need to cooperate with the Brazilian meteorologists. We would not be surprised to find material transported in the "wrong" direction or ships encountering strong currents where none were known. For each industrial, recreational or defense use of the ocean, new data are required; new understanding needs to be sought. The new data bases from ships, moorings, satellites and other platforms have posed many new questions while answering few of the old ones.

Oceanography, as all natural sciences, progresses by discovery of ideas and invention of tools. The history of science is interlinked with the closely coupled system of instrument, data, idea and theory. There are discoveries in oceanography due to theory. But they are rare. Usually, we have an observation; such as there is a Gulf Stream; then we collect data on the current; then a theoretician tells us why there must be a Gulf Stream. However, the theory doesn't tell us everything we can observe. Usually, the theory is linear and can be handled with classical mathematics. Unfortunately, the ocean is turbulent and, consequently, non-linear. If we desire further understanding, it is necessary to use computers for our calculations. Even if the model is linear, we need to resolve the scales of the ocean currents and the actual shape of the basin which requires extensive computer power.

It is trivial to state but fundamental to recognize that the ocean moves. Therefore it transports from location to new location, from bottom to top, its contents. It transports heat, salt, CO_2, oxygen, living things, dead things, waste, minerals, gases, etc. There was a time when it was fashionable to believe that except for tides and waves, the currents of the ocean were independent in time. One could put a note in a bottle and send it to an unknown place. If you learned that the bottle arrived, you could repeat the experiment. It is now well known that this is not true. The space and time variability of ocean currents, rather than the steady flow, is the dominant feature. The variability of oceanic phenomena cannot be adequately understood without extensive calculations using modern computers, and without an understanding of the motion, one cannot expect to understand such phenomena as the life in the ocean or the ocean's role in climate.

A recent National Academy of Science report entitled, "Workshop on Ocean Models for Climate Research," describes many on-going ocean modelling activities. In the present report in Appendix D we discuss the potential application of ocean models for national needs and Appendix E reviews several types of ocean models.

The reader must have asked by now: Why giant, expensive computers? The answer requires some explanation. In comparison to the atmosphere, the ocean space variability exists on smaller space scales, but the time variability is longer. An atmospheric mid-latitude cyclone has a horizontal scale of a few thousand kilometers and lasts a few days. An oceanic Gulf Stream Ring has a horizontal scale of several tens of kilometers and can exist for a few years. Therefore, an ocean modeller needs smaller grid sizes and more time steps to simulate the ocean.

Numerical models idealize the environment by dividing up the ocean region to be modelled into horizontal and vertical grid boxes. Each variable such as velocity, temperature, or salinity, has one value for each timestep in each box. The reader might wish to calculate how many boxes of size 10 km x 10 km x 1 km are contained in the North Atlantic. The size of each box should be determined by the expected horizontal scale of variability to be modelled. However, in both meteorology and oceanography it is often determined by the the speed and capability of the available computer resources.

The numerical approximations of the partial differential equations describing the physics and chemistry of the ocean reduce the equations to non-linear algebraic equations. The equations link dependent variables for each box with the behavior at neighboring boxes. If a model has, say, 6 variables and there are 10^4 boxes, we must solve 6 x 10^4 linear algebraic equations at each time step.

Can we take a very large time step? The answer is no. Information theory tells us that a parcel of water or a wave crest may not pass any grid box during one timestep in our calculations. Stability analysis theorems demonstrate that the calculations are absolutely unstable if we violate this principal. The calculations "blow up", i.e., infinitely large oscillations occur. In simple terms the product of the fastest speed in the model times the timestep must be less than the distance between boxes. For many problems, ocean modellers filter out very fast waves such as sound waves and external gravity waves. The resulting models are so-called primitive equation models. If we filter out internal gravity waves, we obtain quasi-geostrophic models. There are other classes of models. For calculating the weather in the ocean and the currents, one typically uses a timestep of 1-10 hours. The number of timesteps in typical models is 10^3-10^5 timesteps for one calculation.

The simplest formula for calculating the amount of computer time for a particular model is:

Computer Time = No. of Grid Boxes
x No. of Time Steps
x No. of Operations per Grid Box per Time Step
÷ No. of Operations per sec.

Let this be rewritten

$$\text{Computer Time} = G \times T \times O/S$$

Suppose we have $G = 10^4$ boxes and $T = 10^4$ timesteps. It can be shown that for a three dimensional model, O, the number of operations per grid box per time step is 2000-3000, depending on the number of variables and number of physical processes contained in the problem. S is our computer speed. At many university computer centers, $S = 1 \times 10^6$ operations per second. A modern class 6 machine (1), $S = 100 \times 10^6$ operations per second.(2) For our sample problem, one run at a good university computer center takes 5-6 hours, while on the fast machine we use 2 minutes. Clearly, we cannot do many calculations that require several hours per run.

In this report we summarize the estimates of the entire U.S. theoretical oceanographic community with regard to their projected and desired requirements for 1984. We expect that each scientist has done a calculation similar to the above to reach his projection.

The entire U.S. ocean modelling community was surveyed to arrive at an estimate of present resources and future requirements. The hardware needs and the available manpower were assessed. We did not include resource requirements for analyzing very large data sets from remote sensing experiments planned for the late 1980's. These needs are even more computer oriented than the modelling efforts. We have, however, reviewed the available computer technology to assess future changes in computer configuration and performance.

Footnote

(1) A class 6 machine is a computer with speed exceeding 50 million floating operations per sec and usually has a high speed memory of at least 1 million words.

(2) The term MIPS, or million of operations per second, was used for operational speed of sequential computers or scalar machines. Modern class 6 computers use MFLOPS or million of floating point instructions per second. These vector processing machines complicate the estimation of computer time since speed depends critically on computer code structure.

PRESENT AND FUTURE RESOURCES AND REQUIREMENTS

The primary task of the Committee was to estimate and to evaluate the computational resources needed to sustain scientifically-desirable progress in ocean dynamics and circulation modelling during the decade of the 1980s. Of particular concern was a determination of any discrepancy between the computing resources required by the community of theoretical oceanographers and the resources available to them from present and planned facilities. Estimates were therefore needed not only of the anticipated future level of oceanographic modelling activities, but also of the projected availability of resources for these activities. In deriving the latter estimates, account has been taken of advanced technology options which might be available for large-scale scientific computing in the 1980s; this topic is discussed further in a later section.

(A) Estimates of computer resource needs

The Committee itself was comprised mainly of experts in various aspects of ocean modelling. At its first meeting in November 1979, the group discussed the types of problems in ocean science for which numerical solution techniques were needed and the resulting requirements in terms of computer resources. The preliminary conclusion was that a substantial fraction of a class 6 computer system could be justified and utilized for the solution of a broad range of oceanographic problems. In order to refine further their own estimates with independent data, the Committee decided to poll directly the community of ocean modellers. An initial letter of inquiry was mailed in November, 1979, to 32 representatives of institutions and/or groups which are presently involved in ocean dynamics and modelling. The letter requested the following information: (1) the approximate number of full time equivalent (FTE) ocean modellers in the respondee's group, department, or institution;

(2) estimates of computer resources currently being used and needed in future for the group's research; and (3) the location and type of the machines on which this research is currently being carried out.

A second letter in March 1980 was sent to clarify further the terms in the original survey and to give the responding groups a chance to modify their estimates. The groups were also advised of the Committee's intention to document their final report with the estimates provided by individuals and individual institutions. On the basis of a total of 31 responses, including new or corrected information received in response to the second letter, a final data base on computer resource needs in oceanography was compiled. The complete results of this compilation, given in Appendix A, are summarized below.

To give a breakdown of the anticipated future effort into different oceanographic research areas, resource need estimates were requested for each of several ocean model types: climate and coarse-resolution oceanic general circulation models (OGCM/climate), quasi-geostrophic and primitive equation eddy-resolving general circulation models (EGCM), and regional/process models (including models of the equatorial and coastal regions). Resource estimates for conventional data processing and other uses, such as pollution studies, tracer studies and observing system tests, were also tabulated. No estimates of computer resources for data analysis of satellite systems were requested, since the Committee felt this was not part of its task. Some of the modelling areas necessarily overlap; the appropriate classification of work within the model categories was left to the individual respondees. Further discussion of the scientific problems associated with each model class, as well as some assessment of computational requirements, is given in the appendices. For each model class, the following estimates were requested: (1) the present level of computer use, (2) the projected usage for calendar year 1984, and (3) the desirable level of usage (in 1984) for ocean modelling research considered to be genuinely valid but limited by resources. As defined in the second mailing, "desirable" was taken to mean "scientifically desirable and feasible for your group, including intended manpower changes and assured computational resources on a class six machine."

The responses to the survey have been tabulated in Appendix A as a function of model category according to present, projected (1984) and desirable (1984) computing requirements. In the case of a group using more than one computer, the net usage is expressed in units of CPU hours per year for the highest level computer mentioned. Total usage at each installation has been converted to CRAY-1 hours since this community is familiar with the NCAR CRAY-1. In performing these conversions, we have used the factors listed in Appendix B.

Cumulative usage at all institutions is shown in Table 1a; for purposes of later comparison with available computational resources, the separate components of usage at federal laboratories and at universities (including NCAR) are shown in Tables 1b and 1c. The latter tables show approximately equal resource needs in federal laboratories and universities after summing over model categories. As the overall usage estimates indicate (Table 1a), projected usage for ocean dynamics and circulation modelling in 1984 is more than twice as large as present levels. Furthermore, achieving a "desirable" level of ocean modelling research will require a fivefold increase in computer resources for oceanography between now and 1984. The disparity between the "projected" and "desirable" categories also indicates that ocean modellers are limited, or believe that they are limited, in their future

Table 1. Present, projected and desirable resource needs for ocean circulation modelling (units: cpu hours/year on a class six system)

(1a)
Usage at all Installations

	Present	Projected	Desirable
OGCM/Climate	260	1167	2587
EGCM	309	643	1222
Regional/Process	615	1368	2462
Data/other	324	926	1332
TOTAL	1508	4104	7603

(1b)
Usage at Federal Laboratories

	Present	Projected	Desirable
OGCM/Climate	157	659	814
EGCM	68	197	197
Regional/Process	266	763	1351
Data/other	250	773	1102
TOTAL	741	2392	3464

(1c)
Usage at Universities and NCAR

	Present	Projected	Desirable
OGCM/Climate	103	508	1773
EGCM	241	446	1025
Regional/Process	349	605	1111
Data/other	74	153	230
TOTAL	767	1712	4139

research by the availability of computational resources. The extent to which this is the case will be examined below.

Table 2 shows the number of institutions and associated FTEs whose present, projected and desirable resource need estimates fall with the nominal intervals 0-25, 25-100, 100-200, 200-500, and >500 cpu hours per year. This breakdown indicates that the majority of institutions presently use less than 25 (class-six) cpu hours/year each. If computational resources were adequate to accommodate the "desirable" level of ocean modelling activity in 1984, it is estimated that the prominent peaks in institutional usage would occur in the (25-100) and (200-500) cpu hours/year intervals.

(B) Estimates of computer resource availability

Present and projected resources available for use by the oceanographic modelling community are tabulated in Table 3; resources available for modelling at government laboratories (3a) and at academic departments (3b) are separately listed. These figures have been provided by Committee members from the listed institutions (or by consultation with appropriate corresponding members of this committee) and reflect committed increases in computer power and/or larger fractional allocations to oceanographic projects. In addition, an increase in local computing capabilities of one-half has been assigned to the universities as a result of expected hardware upgrades and a general increase in ocean modelling activity.

At present, in addition to resources available locally at universities, resources for ocean modelling in the academic community are made available predominantly by two facilities: the National Center for Atmospheric Research (NCAR) and the Goddard Laboratory for Atmospheric Sciences. As shown in Table (3b), present and projected resources for academic research in ocean dynamics and circulation modelling total 700 and 1000 cpu hours/year, respectively.

Table 2. The numbers of institutions/FTEs with resource need estimates within the given interval.

	cpu hours/year				
	0-25	25-100	100-200	200-500	>500
Present	16/72	12/89	1/6	2/12	0/0
Projected	9/41	11/63	6/34	4/34	1/6
Desirable	5/19	12/56	3/33	8/52	3/19

Table (3a)

Resources available for ocean modelling at federal laboratories

	Present	Projected
GFDL	430	1260[†]
DOD	75	270
GLAS	110	490
OTHER	85	380
TOTAL	700	2400

Table (3b)

Resources available for ocean modelling at universities and NCAR

	Present	Projected
Universities	135	200
NCAR	500	500
GLAS	65	300
TOTAL	700	1000

[†]1260 cpu hours/year is equivalent to 15 percent of a (1.5 class six) system, and represents the panel's estimate for the power of the anticipated GFDL system. November 1980.

The analogous cumulative figures for oceanographic modelling at government laboratories are 700 and 2400 cpu hours/year. Note that, while resources for ocean modelling at federal installations are expected to more than triple, resources for academic oceanic modelling work are not expected to increase greatly.

Comparison of Tables 1 and 3 - showing the estimated computational needs versus the expected resources - indicates a substantial shortage in computing resources by 1984. Table 4 gives the relevant figures. Although some shortage with respect to "desirable" oceanographic modelling at federal laboratories is indicated, our survey suggests that *planned computer resources will be adequate for the needs of federal laboratories in 1984 in the area of scientific ocean modelling*. The situation for the academic community is less promising. The figures presented here indicate that resources for oceanographic modelling at academic institutions will be inadequate to support not only the "desirable" level of modelling activity but also the more modest "projected" research level. In particular, *the projected computing resources of the academic ocean modelling community will fall short of their projected needs in 1984 by a factor of 2, and will fall short of a scientifically feasible and desirable level of use by a factor of* 4. The indicated shortage is approximately equivalent to the resource provided by a large fraction of one class 6 computing system.

Whereas government facilities expect to grow to accommodate a two-to-four-fold increase in their oceanographic modelling, we conclude that the academic modelling community can presently expect only a small and inadequate increase in the total resources available to it. *To ensure the advancement of oceanography as a science, there is a requirement for a class 6 computer facility by 1984 which is available for use by the academic community.*

Table 4. Projected shortage in resources available for ocean modelling in 1984. [Figures are obtained by subtracting total usage (Table 1) from total available resources (Table 3).]

	Present	Projected	Desirable
All Institutions	108	704	4203
Federal laboratories	41	-8	1064
Universities and NCAR	67	712	3139

The Committee, on the basis of its own expertise in ocean modelling, feels that the results of the survey are fair estimates of genuine resource needs in confirmation of their own earlier estimates. (Further information on the nature of the scientific problems which require increased computational resources is available in Appendix E.) The Committee endorses the conclusions of the survey on the basis of its own critical examination of the scientific issues.

MANPOWER RESOURCES

An adequate number of ocean modellers will be available to utilize effectively the computer resources that would be available to the ocean modelling community in 1984 if the computer resource shortage is eliminated. A total of 180 FTE ocean modellers were identified in 32 institutions which responded to the panel's questionnaire, including Ph.D's and equivalents and graduate students who are engaged actively in research. An FTE ocean modeller was defined as "a theoretical dynamicist and/or numerical modeller including graduate students at the research level, and programmers with an independent research responsibility and a Ph.D. or equivalent," and counted as 1 or 1/2 according to the amount of time devoted to ocean modelling. The panel itself counted 88 Ph.D. ocean modellers known to its members to be working at the 25 major modelling institutions. Of these 88, about half were identified as having attained their doctorates within the last 5 years (1975-1980). These new Ph.D. oceanographers are well trained in modern statistical and mathematical techniques. Almost all the new personnel have the training to appreciate and use the results of ocean model studies to plan their work, analyze the model data and assist in design studies for oceanographic field programs. (All of the 88 ocean modellers are not planning to use very large and expensive models.) This doubling of the number of modellers quantifies the recent rapid growth of the field, and, in the opinion of the panel, is contributing substantially to the stressing of the presently available computing resource. *There has been a doubling of Ph.D. ocean modellers in the past 5 years and there exists now adequate manpower for effective utilization of new computer resources.* The experience of the atmospheric modelling community indicates that even though a class 6 machine can support several hundred people, use at any given time is dominated by a group of about 30 scientists. The 7000 hours estimated as being scientifically desirable and feasable by 1984 is equivalent to 1.5 class 6 machines. At a growth rate of 10 new Ph.D. ocean modellers per year the panel estimates that about 250 FTE's will be working in the field by 1984. This personnel resource is more than adequate to exploit fully a recommended computer resource. The 180 FTE's existing today include 78 FTE's working in 14 groups that have large models: 10 of these groups comprising 58 FTE's are academic. Thus the present population of modellers already constitutes an adequate group. The NAS has recently completed an extensive survey of manpower in oceanography (Doctoral Scientists in Oceanography, National Academy Press, 1981).

TECHNOLOGY ASSESSMENTS

A. Computational Requirements for Ocean Modellers

The requirement for a computer system to perform a very large number of computations in a reasonable length of time has been described in other parts of this report. But what is less obvious is that in order to take advantage of a massive amount of computation power, major additional facilities must be provided. A computing system for large-scale modelling should include the following:

* the capability to do rapid numerical computations
* the capability to manipulate and archive large volumes of numbers
* the capability to graphically (and preferably interactively) interpret the simulations.

As an illustration, an EGCM computation can be characterized as having:

100,000 grid points

2-4 variables/grid point

1-2 seconds computation time(1)/time step

50,000 time steps/case study

histories saved every 50 steps

Ocean GCM's can be even more demanding in terms of the number of grid points and the computation time. The implications of these numbers is not just that cases can take 20 hours of Class 6 processor time, but also that a case can produce for further analysis several hundred million numbers. It is the manipulation and archiving of these data sets as well as the graphical analysis of the data that is behind the need for a broadly based system architecture. While seemingly expensive in terms of people and equipment, the cost of doing this is significantly less than the cost of recomputing cases, and the scientific insight gained from carefully planning computations and carefully analyzing the results is immeasurably greater.

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(1) Class 6 computer

B. Present Systems Availability

There is a plethora of systems today that can meet the needs of oceanographic modellers. They range from "superscale" scientific computers[1] to the "supermini"[2] and range in computational power by approximately a factor of 50. Large models run quickest and in some sense, easiest on the superscale computers. Large scale data processing (the data set manipulation and archiving function) is perhaps most convenient on large-scale commercial systems built by such companies as IBM[3], Burroughs, Univac, Amdahl and Control Data. The "supermini" can be a fine tool for interactive graphics.

This is, of course, somewhat simplistic. While each class of computer systems is tailored to specific functions, all are general purpose systems, and can take on other functions. That is, a "supermini" can execute a large model but at the cost of taking weeks instead of hours. A "superscale" computer can do graphics, but it would undoubtedly be too expensive to let the user do interactive graphics. The best solution technically is to have a mix of systems that are functionally tailored.

There are other issues, however, that should be considered. One is the extent to which computing power should be distributed throughout the university oceanographic modelling community. For example, the following alternatives are worth considering:

* establishment or augmentation of a single national center
* establishment or augmentation of regional centers
* local systems acquired by individual scientific groups
* some combination of the above.

1. Characterized by such Class 6 computers as the Cray Research, Inc. Cray-1S or the Control Data Corp. Cyber 205.
2. Characterized by the Digital Equipment Corp. VAX 11/780
3. Characterized by the IBM 303x series.

The national centers can be characterized by those at the National Magnetic Fusion Energy Computer Center (NMFECC). They each service a community of 500-1,000 users. Almost all users can communicate remotely and have a limited amount of computing power available locally. Widespread use of local systems is characterized by the university chemistry community, although there is a National Resource for Computation in Chemistry (NRCC) to exchange software information and dispense limited grants of computer time on a Class 5 system. Broadly speaking, one mode of operation is to have small groups restricted to having a moderate amount of computer power available, but having the ability to "tune" their system appropriately and "govern" it themselves. The other mode is to have general access over communication links to massive amounts of computer power, but having to deal with a larger and less flexible organization. The regional center seems to get the worst of both worlds -- being unable to take advantage of the economies of scale, while being unable to remain small and flexible. However, small local operations also suffer all the management problems of larger facilities once the number of users gets beyond a half dozen or so. A variety of systems seems to be the best solution.

Rough representative costs in 1981 $ are:

	Capital Costs	Operating Costs/Yr.	Operating Costs with Capital Costs Amortized over 5 years
National Center	$15M	$3M	$6M
Local Facility	$500K	$100K	$200K

Where M = 10^6 and K = 10^3. Systems costs include peripherals, archival and graphical facilities for a limited community of users. The capital costs for a national center were estimated by assuming:[(1)]

Class 6 Computer	\$9.0M
Archival System	2.0
Data Processing System	2.0
Communications	.5
Graphics	.5
Space & Miscellaneous	1.0
	\$15.0M

Performance ratios between "national" and "local" systems are roughly 50 for numerically intensive codes (based on memory bandwidth, not on functional unit speeds) and a similar figure for the processing and archiving of data (based on sustained use of disk and tape channels).

Augmenting existing facilities would be considerably less. Capital costs and operating costs are approximately 60% and 30% of the respective figures for establishing new facilities. This assumes that only a few additional people would be required for the national center and more for a local facility.

Additional considerations which favor a national facility are:

* availability of facilities to all oceanographers
* availability of specialized software and consulting
* a centralized location for researchers to meet and exchange information, with a centralized archive
* ability to perform the very largest computations in a reasonable period of time.

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(1) A similar estimate was calculated by the physics community Subcommittee on Computational Facilities for Theoretical Research in "Prospectus for Computational Physics", National Science Foundation, 1981.

C. Expected Performance Improvements, 1980-84

Technology advancements in the next few years will be heavily dependent on the demands of the commercial marketplace, since this dominates the scientific/engineering computer market. Consequently, it is expected that no new radical architectures or materials will emerge until the late 1980's. Progress will continue to be evolutionary, with concomitant changes in pricing, offset by the effects of inflation. Incrementally, more powerful systems will become available in the 1980-84 time frame, but price/performance ratios will not decline dramatically. Radical performance improvements are not expected until after 1984.

With a declining cost in logic, architectures will evolve toward multiprocessor configurations. This will permit phased upgrades of systems, and will be true of the "superminis" as well as larger systems. However, significant difficulties will remain in segmenting codes to run in parallel on more than one processor. If memory demands continue to escalate, system hardware costs may increase rather than decrease. Software and maintenance costs will rise at greater than the inflation rate due to shortages in trained personnel. Thus, it is expected that equipment prices may increase somewhat (most manufacturers raised prices in 1980) and operating costs will increase substantially.

RECOMMENDED RESOURCES FOR OCEAN MODELLING

The physical oceanography modelling community is now at a critical junction in its progress. This report documents the various scientific and practical uses of investment in ocean modelling. It appears that considerable advances can be made by investing in readily-available computer hardware for the oceanographic community.

The unavailability of adequate computer time in the U.S. is almost unique amongst developed countries. Despite reports of severe economic problems in Britain, ocean scientists in the United Kingdom have access to several class 6 machines. Both research and academic oceanographers have easy access to several large computers located throughout Britain. In West Germany the situation is also bright. Oceanographers at Kiel and Hamburg, e.g., have available class 6 machines for their models. In the Soviet Union there are only medium size computers and their ocean models are also modest. Both France and Norway have plans to acquire class 6 machines in 1983. In Japan, ocean modellers at the University of Tokyo have easy access to a class 6 machine. Recent Japanese visitors to the U.S. have commented to the chairman about the quality and size of the computers.

In short, the U.S. is falling behind. The NCAR computer facility is saturated; the new resources available for academic ocean modelling at Goddard will not fulfill the requirements for computing resources for the ocean modelling community.

The committee recognizes that support for academic ocean modelling is split between several agencies; NSF, NASA, NOAA, DOD, Energy, BLM, etc. We are not willing to recommend how these diverse organizations with widely varying missions might react to a particular recommendation for supporting a new computer capability for ocean modelling. We do recognize, however, that several years of planning are required to acquire a large machine.

We do recognize that a new large computing facility for oceanography cannot be located arbitrarily. The committee recommends that the new facility should be co-located with a center with experience in large scale computing. This includes several university sites, NCAR, Goddard, various DOD laboratories, etc. It is expected that these existing centers would have a cadre of software, graphics and experienced computer programmers and computer scientists to assist the new organization.

It is not obvious to the committee what the exact next step is in the planning and acquisition of large computing resources for ocean modelling. It has been apparent to the committee, its corresponding members and our colleagues in the oceanographic community that computer resource shortage is real. The technology is readily available. Exciting advances in understanding the ocean can be achieved if the computer time is made available. We expect that rapid advancement and improved practical application of physical oceanography will ensue as we have seen in Physics, Chemistry, Meteorology, Geology, Geophysics and other disciplines if the computing resources and facilities for ocean circulation modelling are acquired.

This logically leads us to our first recommendation.

RECOMMENDATION 1

In view of the scope and magnitude of the needed computation resources, we recommend that the resources of a class 6 system or equivalent be established for ocean modelling research. It should be a computing resource accessible for use on a scientific merit basis by the entire academic ocean modelling community of the U.S. The allocation of the resources should be the responsibility of the oceanographic community.

There are several parts to this recommendation. We have documented the requirement for a class 6 machine. We have not addressed the management of the resource. In these times of limited economic support for science, it is important that the best science be supported and the most outstanding ocean models be funded. Therefore it is recommended that the new computing resource be available on scientific merit to the entire academic ocean modelling community in the U.S.

In order to ensure proper utilization of the resource, a review structure managed by the oceanographic community needs to be established for distribution of the computing resources. In the past, the atmospheric science community have been kind enough to allow academic ocean modellers to use the computers at NCAR, Goddard, GFDL, etc.

The second task for the committee was to recommend mechanisms for providing the required new computing resources. To a large degree we are sidestepping this issue and recommending instead:

RECOMMENDATION 2

> *Whereas adequate resources are not now available or being planned, and in view of the lead time required in their acquisition, we recommend that planning begin without delay to provide the necessary computing resources.*

APPENDIX A. INSTITUTIONAL ESTIMATES OF COMPUTER NEEDS

GROUP	U WASH	PMEL	OSU ATM	OSU OCN	SIO	NPS	SANDIA	NCAR	WHOI(A)	GLRC	TEX A&M	NORDA
PERSONS	4.5	5.0	3.0	7.0	7.0	7.0	3.0	5.5	6.0	4.0	7.0	14.0
MACHINE	CRAY I	CDC 6500	CRAY I	CYBER	PR 1750+	360/67	CDC 7600	CRAY I	CRAY I	CDC 6600	AMDAHL6 II	ASC2
SPEED	.040	.040	1.000	.200	.100	.050	.200	1.000	1.000	.040	.150	.300
OGCM	0	0	10	0	0	500	0	0	0	0	0	10
QG EGCM	2	0	0	0	110	0	10	120	5	0	0	30
PE EGCM	0	0	0	0	0	0	2	20	0	0	20	120
EQUATOR	0	0	10	0	0	0	0	30	0	0	0	20
CLIMATE	2	18	10	0	0	0	0	50	0	0	0	0
COASTAL	2	36	0	0	0	10	0	0	5	100	80	0
REGIONS	4	36	0	0	40	100	18	20	10	50	0	20
DATA	0	0	0	60	0	75	2	5	0	50	20	0
OTHER	0	24	0	15	0	15	5	0	0	0	0	50
PRESENT LEVEL OF CRAY-EQUIVALENT USAGE	10.00	4.56	30.00	15.00	15.00	35.00	7.40	245.00	20.00	8.00	18.00	75.00
OGCM	0	0	25	0	0	2000	0	0	0	0	0	300
QG EGCM	2	0	25	0	160	0	100	100	10	0	0	60
PE EGCM	0	0	40	0	0	0	20	40	0	0	20	240
EQUATOR	0	0	40	0	0	0	0	20	0	0	0	100
CLIMATE	2	24	60	0	0	0	0	100	0	0	0	0
COASTAL	2	48	0	0	0	20	0	0	10	300	80	0
REGIONS	4	48	0	0	40	500	20	20	20	150	0	100
DATA	0	0	0	100	0	300	10	10	0	150	40	0
OTHER	10	36	0	30	0	30	10	0	20	0	0	100
PROJECTED (1984) LEVEL OF CRAY-EQUIVALENT USAGE	20.00	6.24	190.00	26.00	20.00	142.50	32.00	290.00	60.00	24.00	21.00	270.00
OGCM	0	0	50	0	0	20000	0	200	0	0	0	300
QG EGCM	2	0	50	50	260	0	100	200	20	0	0	60
PE EGCM	0	0	80	20	0	0	20	100	50	0	200	240
EQUATOR	0	0	80	0	0	0	0	40	0	0	0	100
CLIMATE	2	24	120	0	0	0	0	100	50	0	0	0
COASTAL	2	48	0	0	0	40	0	0	20	600	160	0
REGIONS	4	48	0	0	40	5000	20	40	20	300	0	100
DATA	0	0	0	100	0	600	10	20	0	300	80	0
OTHER	20	36	0	30	0	30	10	0	50	0	0	100
DESIRABLE (1984) LEVEL OF CRAY-EQUIVALENT USAGE	30.00	6.24	380.00	40.00	30.00	1283.50	32.00	700.00	210.00	48.00	66.00	270.00

GROUP	FSU	MIAMI	AOML	GFDL	GLAS	PRINCET	NOAA DC	MID-ATL	SAI	U CHIC	ARGONNE
PERSONS	8.0	5.0	5.0	6.0	6.0	1.5	2.0	20.0	6.0	1.5	3.0
MACHINE	CRAY I	CRAY I	UN 1108	ASC4	AMDAHL6 II	ASC2	370/195	CRAY I II	ASC2	370/168	370/195
SPEED	1.000	1.000	.030	.500	.150	.300	.200	1.000	.300	.080	.200
OGCM	0	0	0	0	0	0	0	0	0	0	0
QG EGCM	0	0	0	0	100	0	0	0	0	0	0
PE EGCM	0	60	0	0	0	0	0	0	20	0	0
EQUATOR	15	0	0	180	30	0	0	0	0	0	0
CLIMATE	5	0	10	300	20	0	0	0	0	0	0
COASTAL	40	10	200	0	0	60	25	38	0	10	0
REGIONS	2	0	200	180	100	5	0	2	0	0	100
DATA	0	0	175	24	100	0	0	11	0	0	50
OTHER	0	0	220	180	400	0	0	0	0	0	0
PRESENT LEVEL OF CRAY-EQUIVALENT											
USAGE	62.00	70.00	24.15	432.00	112.50	19.50	5.00	51.00	6.00	.80	30.00
OGCM	50	0	0	0	0	0	0	0	0	0	0
QG EGCM	0	0	0	0	0	0	0	0	0	0	0
PE EGCM	0	60	0	0	350	0	0	0	100	0	0
EQUATOR	35	0	0	540	100	0	0	0	0	0	0
CLIMATE	35	60	10	900	650	0	0	0	0	0	100
COASTAL	30	10	300	0	0	100	25	55	0	10	0
REGIONS	10	0	265	540	200	20	0	3	0	0	300
DATA	0	0	225	72	100	0	0	14	0	0	150
CTHER	0	0	430	540	1860	0	0	0	0	0	200
PROJECTED (1984) LEVEL OF GRAY-EQUIVALENT											
USAGE	160.00	130.00	36.90	1296.00	489.00	36.00	5.00	72.00	30.00	.80	150.00
OGCM	20	0	0	0	0	0	0	0	0	0	0
QG EGCM	0	0	0	0	0	0	0	0	0	0	0
PE EGCM	100	120	0	0	350	0	0	0	100	0	0
EQUATOR	5	0	0	810	100	0	0	0	0	0	0
CLIMATE	30	60	10	1350	650	0	0	0	0	0	200
COASTAL	100	10	300	0	0	200	100	84	0	10	0
REGIONS	30	0	265	900	200	40	0	3	0	0	600
DATA	0	0	225	72	100	0	0	18	0	0	300
OTHER	0	0	430	810	1860	0	0	0	0	0	400
DESIRABLE (1984) LEVEL OF GRAY-EQUIVALENT											
USAGE	285.00	190.00	36.90	1971.00	489.00	72.00	20.00	105.00	30.00	.80	300.00

GROUP	BKHAVEN	YALE	CG ACAD	URI	HARVARD	MIT	WHOI(B)	CEM	U MAINE
PERSONS	4.0	6.0	2.5	5.0	8.0	8.0	6.0	3.0	4.0
MACHINE	CDC 7600	DEC 20	CRAY I	AS/5	AMDAHL6	AMDAHL6	VAX 11	CRAY 1	IBM 3031
SPEED	.200	.020	1.000	.040	.150	.150	.020	1.000	.040
OGCM	0	0	0	0	0	0	0	0	0
QG EGCM	0	0	0	0	0	100	150	0	0
PE EGCM	0	0	0	0	0	0	0	0	40
EQUATOR	0	150	0	0	0	30	0	0	0
CLIMATE	0	50	0	0	0	0	0	0	0
COASTAL	25	0	36	250	0	0	75	5	20
REGIONS	0	0	0	120	170	0	400	20	0
DATA	10	0	10	80	30	100	50	0	0
OTHER	150	0	0	0	0	0	75	0	0
PRESENT LEVEL OF CRAY-EQUIVALENT USAGE	37.00	4.00	46.00	18.00	30.00	34.50	15.00	25.00	2.40
OGCM	0	0	0	0	0	0	0	0	0
QG EGCM	0	0	0	0	350	0	250	0	0
PE EGCM	0	0	0	0	0	600	0	0	70
EQUATOR	0	150	0	0	0	0	0	0	0
CLIMATE	0	50	0	0	100	400	0	0	0
COASTAL	50	0	0	300	0	0	150	20	40
REGIONS	0	0	30	300	300	500	800	50	0
DATA	10	0	10	100	100	100	100	0	0
OTHER	200	0	0	0	0	0	200	0	0
PROJECTED (1984) LEVEL OF CRAY-EQUIVALENT USAGE	52.00	4.00	40.00	28.00	127.50	240.00	30.00	70.00	4.40
OGCM	0	0	0	0	0	0	0	0	0
QG EGCM	0	0	0	0	600	0	250	0	0
PE EGCM	0	0	0	0	0	900	0	0	70
EQUATOR	0	500	0	0	0	0	0	0	0
CLIMATE	0	50	0	0	200	700	250	0	0
COASTAL	500	0	0	500	0	0	150	20	40
REGIONS	0	0	60	500	300	500	800	50	0
DATA	50	0	10	150	100	100	100	0	0
OTHER	750	0	0	0	0	0	200	0	0
DESIRABLE (1984) LEVEL OF CRAY-EQUIVALENT USAGE	260.00	11.00	70.00	46.00	180.00	330.00	35.00	70.00	4.40

APPENDIX B

Relative Computer Efficiency

Machine	Relative efficiency of CPU for ocean models
CYBER 205-411	1.50
CRAY1	1.00
TI ASC4	0.50
TI ASC2	0.30
CDC 7600	0.20
CYBER 176	0.20
IBM 370/195	0.20
Amdahl V/6	0.15
Prime 750 (+ array processor)	0.10
IBM 3032	0.08
IBM 360/67	0.05
ITEL AS/5	0.04
CDC 6600	0.04
IBM 3031	0.04
Univac 1108	0.03
DEC 20	0.02
VAX 11/780	0.02
CDC 7400	0.02
PDP 11/60	0.01

Appendix C

List of Oceanographic Institutions contacted

University of Washington, Oceanography Department
Pacific Marine Environment Laboratory, NOAA
Oregon State University, Atmospheric Sciences
Oregon State University, Oceanography Department
Scripps Institution of Oceanography
Naval Postgraduate School
Sandia Laboratories
National Center for Atmospheric Research
Woods Hole (NCAR computing)
Great Lakes Research Center (NOAA)
Texas A&M University
NORDA, Bay St. Louis
Florida State University
University of Miami
AOML, Miami (NOAA)
GFDL, Princeton (NOAA)
Goddard Laboratory for Atmospheric Science
Princeton University
NOAA, Washington Area
Mid-Atlantic Universities
Science Applications, Inc.
University of Chicago
Argonne Nat'l Laboratory
N.Y. Coastal Modellers (Brookhaven)
Yale University
Coast Guard Academy
University of Rhode Island
Harvard University
MIT Oceanography/Meteorology
Woods Hole Oceanography Institution (local)
Center for Environment and Man
University of Maine

Total # Contacted: 32

Appendix D

A Review of National Needs

As our knowledge of ocean science advances, problems of national importance which involve the broad scientific and practical exploitation and application of this knowledge are being identified and attacked. These problems relate to the nation's economy and security and effect the health and safety of our citizens. The necessity for research in ocean science for national needs was recognized by the Office of Naval Research and the Stratton Report in 1959. The national effort has included, e.g., the establishment of the National Oceanic and Atmospheric Administration (NOAA). Oceanography involves the conduct of very large scale, research programs initiated under the IDOE of the NSF in 1970 (NAS reports 1969, 1979). A report just issued by NACOA "Ocean services for the Nation" 1981 details some pressing contemporary national requirements. Ocean currents and circulation are of practical societal interest; for example, ocean currents are important as a <u>transport mechanism</u> for water properties and chemicals as well as dissolved and particulate matter, inorganic (living and dead). Examples of transports of interest include heat, chemicals, sediments and pollutants.

Models summarize and extend our knowledge of the circulation. They provide the conceptual basis for coupling physical oceanography to interdisciplinary scientific and technical problems in a quantitative way. Computer models provide the only means of dealing with the complex geometry, forcing and other inputs which characterize real ocean situations. Models provide a means of simulating ocean processes and therefore allowing estimates of effects, statistically or on a case by case basis, even when insufficient field data exists. Forecasts of the future state of the ocean usually involve models, both for predicting the near future -- e.g., for navigation or military operation or year to year changes that effect weather -- and for longer time scales such as those involved in climatic changes. Furthermore, computer models are rapidly becoming the basic research tool in modern oceanography for the design and interpretation of observational programs and field experiments. Thus, these models play a central and crucial role in the application of modern ocean science to national needs and this role, as modelling itself, is novel, evolving, expanding and increasing. *There are important National programs involving ocean science that require an accelerated development and application of ocean models.*

Fisheries represent a vital resource of the sea and models now play a substantial role in fisheries management and in research on related fundamental scientific questions and development (Fisheries Ecology, NAS, 1980). In fact, biological oceanography generally appears to be on the threshold of major advances which will in an important aspect involving interdisciplinary scientific investigations with physical oceanography and new coupled biological/physical models.

Deep sea mining which is anticipated to be of substantial economic importance will require the development of accurate regional and boundary layer models for engineering and operational purposes. Our nation's energy needs involve the sea in several ways. Energy is transported through the sea, extracted from beneath the sea bottom and from the sea itself in the forms of waves or currents. Oil drilling and spills, the siting and operation of energy production and conversion plants all require modelling.

The management of the quality of the coastal waters of the United States which exchange water and material with the deeper seas beyond the continental shelf is necessary in order to insure the conservation and fruitful exploitation of their resources and the health of our citizens and other people. This involves both dedicated modelling and the application of existing models. These waters and the waters of the deep sea and the world ocean now carry a great variety of man-generated waste materials which have been deposited either deliberately or inadvertently. Waste is or has been dumped from barges, carried by rivers and rain, fallen in after nuclear bomb tests, etc. (Goldberg, 1979). Some wastes cannot be avoided and ocean disposal must be weighed competitively with other possibilities (NACOA report 1981). Modern rational decisions as to the ultimate harm to man or the marine ecosystem prior to such harm occurring necessarily rely in large measure on model predictions. Such models have ocean circulation models coupled directly or parametrically to biological and chemical models. An impressive example relates to the actual or potential disposal of nuclear waste materials in or under the seabed. Low level wastes are already being dumped. This is a serious problem for the U.S. and other nations. Some high-level wastes have a very long life time (10^5 years). This necessitates a hierarchy of circulation models --from source size to the world ocean (Marietta and Robinson, 1981). Pollution problems, which involves the global transport of passive (and active) tracers interface with fundamental research in geochemistry in a symbiotic and important way. The CO_2 climate problem (Climate Research Board, NAS, 1979) is a noteworthy example.

A number of national concerns in the area of security and society require ocean models for forecasting purposes. Disaster and damage from storm surges and hurricane waves can be reduced by predictions. These are also useful for navigation and search and rescue operations. Of particular importance are naval operations which depend upon acoustic conditions in the sea which in turn depend upon the currents and water properties; operational predictions are made in terms of a model coupled with a real/time observational network which is gradually improving in time as our knowledge of circulation modelling improves. In this area as in almost every case above, the use of computer models is doubly essential -- as a research tool and as an operational tool.

The geophysical scientists of the world have identified climate variations as an important research topic. In addition, it is generally believed that the ocean plays a key role in seasonal and interannual climate fluctuations. The prediction of cold winters, dry summers and other climate variability seems to hinge critically on our knowledge of the ocean. This cannot be done easily without an extensive modelling effort. Ocean models for climate are inherently large and expensive due to the long solution time. Some energy companies are presently using class 6 machines for these calculations. The newly acquired computers in NOAA and NASA will be used for these calculations. A comprehensive report on Ocean Models for Climate Research (U.S. Committee for GARP) was prepared for NAS in 1980. This report demonstrates that ocean models for climate research could easily and effectively utilize a substantial portion of a class 6 machine.

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Appendix E

A Discussion of Ocean Models

INTRODUCTION

In the modern scientific world, mathematical models are widely used to increase our understanding of our environment. Oceanographers have used the calculus, differential equations and fluid dynamics to explain phenomena in the ocean for centuries. The earliest computers were designed and used to calculate tides for a myriad of practical uses. As we learned more about the ocean, the need to construct more complicated models has grown. The classical mathematician strives to use analytical techniques to obtain the solution to models. However, these mathematics are limited. The availability of computers has allowed us to consider more sophisticated and realistic models. For example, North Sea scientists have developed sophisticated tide and storm surge models including realistic geometry and topography which can predict on an operational basis the coastal water level if the weather forecast is reasonable. We can also predict wave spectrum and swell accurately over the open sea for commercial and military use given accurate weather forecasts. These are only a few of numerous existing ocean models used in routine service today.

There are new and extremely important national requirements for additional ocean models as discussed in appendix D. In the following, we describe a few of the types of models which are being developed by the international modelling community. The ocean models which calculate the state or circulation of an entire ocean or the world ocean are denoted General Circulation Models. These models occupy the talent and resources of several modelling groups in the U.S. and other nations.

Climate problems require special consideration since they need to be simulated over long time periods. Many practical problems exist in coastal regions and we have included a discussion of the state-of-the-art for coastal dynamics and tides.

There are hundreds of other ocean modelling activities which we have not included. Many of the models not discussed can be done on existing computers such as so-called mixed layer models or inertial motion calculations.

Ocean modelling has developed slowly in comparison to meteorology due to the lack of data for verification. In the past decade, we have had important field experiments which obtained data for model comparison. Due to the lengthly list of national problems which require ocean modelling, it is generally agreed that the U.S. will continue to plan and execute field programs and encourage ocean modelling activities.

In many respects, modelling the ocean is scientifically straight-forward. We know the pertinent equations from fluid dynamics and physics. If we have initial conditions and boundary conditions, it is reasonable to assume that a solution can be calculated. Unfortunately, as in meteorology, the inherent nonlinear and turbulent character of the ocean limits our capability to perform the calculation. We must compromise the complete problem and pose a solvable model. The usual limitation is economics. Even given the largest computers available, it is not possible to perform the calculations we would really like to do. However, there are a wealth of useful theoretical and practical models which can be constructed. In this report we are concentrating on the largest of these ocean models which seem to be amenable to progress if sufficient investment is made in computer resources.

The following is a brief description of ocean modelling for ocean basins, regional problems, climate problems, coastal circulation and tides. Some references are included to aid the interested reader.

OCEAN GENERAL CIRCULATION MODELS

Numerical models which are used to understand the dynamics of three-dimensional oceanic circulations in bounded domains are called general circulation models. Such models can be divided into two categories, depending on whether intended calculations will emphasize the adequate spatial resolution of the physical phenomena or a proper evolution of processes with very long time scales. (It is not possible to have both aspects simultaneously with presently available computing power.) The two types of models will be discussed separately in sections a and b. The models are complementary in many respects. Both types of models have been progressively developed over a period of more than 10 years. In the early developmental stages, great care was taken to prove the correctness of the solution techniques (usually finite-difference methods), in the sense that the results of analytical test problems and laboratory experiments could be reproduced. In this regard, the considerable experience of the meteorological and aerodynamical communities were helpful in accelerating model development.

a. Eddy resolving general circulation models (EGCMs)

It is well known from field observations (the MODE Group, 1978) that vigorous low-frequency circulations exist in the ocean, with length scales close to the internal deformation radius (about 40 km). Theoretical considerations (Gill, Green, and Simmons, 1974; Robinson and McWilliams, 1974) indicate that these motions are analogous to the synoptic disturbances in the atmosphere, which substantially redistribute heat and momentum, both horizontally and vertically, in very complex ways. Because of the limited understanding of these motions from theoretical and observational viewpoints, it is necessary to represent them explicitly in many numerical calculations.

Simulations of basin-wide ocean circulations with resolved eddies are useful for a variety of reasons. With regard to oceanic observations, models assist in the interpretation of existing observational data; and they can be used in the design of future observational programs. With regard to the dynamics of the eddies themselves, models provide complete simulated data sets which can be fully analyzed for dynamical information; they allow an assessment of abstract theoretical ideas within a more complete dynamical framework. As far as the effect of the eddies on the time-mean flow is concerned, the sensitivity of the oceanic circulation to changes in basic eddy parameters (some of which are poorly known from observation) can be determined; competing closure hypotheses for the parameterization of turbulent mixing can be tested. With regard to potential applications, the effect of strong currents and eddies on meridional heat transport (and hence on climate) can be assessed; and transports of biologically and chemically important substances (including pollutants) can be estimated.

Already significant progress has been made in understanding the nature of the oceanic general circulation by means of eddy resolving models. Models have played a dominant role in:

1. identifying the possible sources of eddy energy (Holland and Lin, 1975a, b; Robinson et al., 1977; Semtner and Mintz, 1977; Holland, 1978);
2. reproducing a plausible distribution of eddy energy levels throughout a mid-latitude gyre (Schmitz and Holland, 1981);
3. showing the nature of strong-current instabilities to be very sensitive to governing parameters (Haidvogel and Holland, 1978; Cox, 1979);

4. demonstrating the ability of eddies to drive deep mean circulations (Holland and Rhines, 1980);
5. pointing up the potentially dominant role of bottom friction as a dissipation mechanism (Holland, 1978);
6. indicating the complexity and importance of eddy transports of heat and momentum (Semtner and Mintz, 1977; Harrison, 1978);
7. exploring the possibility of potential-vorticity mixing as a parameterization of eddy processes in some geographical areas (Rhines and Holland, 1979; McWilliams and Chow, 1981);
8. showing fundamental differences between mid-latitude dynamics versus southern-ocean dynamics or equatorial dynamics (McWilliams *et al.*, 1978; Semtner and Holland, 1980).

An enormous amount of computer-intensive work remains to be done if the role of eddies in the general ocean circulation is to be well understood. Present stringent restrictions regarding domain size, grid resolution, generality of the physics, the length of time integrations, and the exploration of parameter space are all related to limited computer time, and need to be overcome if continuing progress is to be made. The interaction of all reasonable physical processes must be considered if confidence is to be had in the results. This includes the effects of bottom topography, coastal configuration, thermohaline forcing, time-dependent forcing, mixing along isopycnal surfaces, very strong non-linearity, and near-surface processes.

b. Oceanic General Circulation Models (OGCMs)

Oceanic general circulation models are used to depict the ocean currents and density structure in a time-averaged sense, without explicitly resolving the energetic mesoscale eddies. Typically, such models are configured to represent the circulation of an actual ocean basin rather than an idealized (e.g., rectangular) basin. Multiple circulation regimes may be involved. The emphasis is on prediction of the long-term equilibrium density field and the sensitivity of that equilibrium state either to parametric changes or to modifications in forcing. These models play a crucial role in understanding many aspects of the large-scale oceanic circulation and in answering important practical questions, as follows:

a. they are capable of representing in a unified manner the important physical processes occurring in various parts of the global ocean (e.g., water mass formation in high latitudes, the maintenance of the mid-latitude thermoclines and gyre circulations, and the representation of upwelling and mean zonal currents in the tropics);
b. as progress on the parameterization of mesoscale eddies takes place using EGCMs, the overall validity of OGCMs will increase;
c. verification of improved representations of the oceanic circulation can be made against the known time-mean fields of temperature and salinity, as well as against the transient distributions of radioactive trace substances;
d. short-term climate variations, now thought to be associated with air-sea interactions in the tropics, can be studied in order to improve long-range weather forecasting;
e. long-term climate changes, such as those related to increased CO_2 in the atmosphere, can be modelled;
f. biological and chemical models can be integrated into the physical models for various scientific and engineering studies.

Significant contributions have already been made by OGCMs to the understanding of the large-scale ocean circulation. These models have begun to show how the ocean transports and stores heat as a vital part of the climatic system (Bryan and Lewis, 1979; Bryan, Manabe, and Pacanowski, 1975; Washington et al., 1980). They have given insights into the formation of the thermocline and deep water masses as well as near surface temperature anomalies (Bryan and Cox, 1967; Semtner, 1976; Haney, Shriver and Hunt, 1978). They have been applied to predict the distribution of geochemical and other tracer substances in the ocean (Holland, 1971; Sarmiento, 1981). In the future they will be needed to give quantitative answers to a large number of questions, spanning a range from intrinsic ocean dynamics to important societal issues involving climate change, pollution control, and oceanic resource management.

The computational requirements of OGCMs are sizable, even though eddies are not explicitly resolved. For example, to do a simulation of Pacific Ocean circulation with adequate horizontal resolution (1° grid spacing) for sufficient time to allow formation of surface and intermediate waters (50 years) would take about 1000 hours on a class six machine.

Ocean general circulation models have always been strongly computer-limited in the past. In order to obtain sufficiently long time integrations, spatial grid sizes have been far too large to represent even time-mean currents adequately or to allow inclusion of crude eddy parameterizations with anything close to the correct order of magnitude. Improved spatial resolution is absolutely necessary if we are going to have confidence in the practical measures suggested by model applications. An example of an important calculation that has tremendous potential significance is the prediction of the oceanic circulation and the associated climate of the Cretaceous period, during which most of the known oil and gas deposits were laid down. A knowledge of the regions of upwelling near the surface with cool relatively anoxic water at depth would identify production regions for organically rich sediments. The vastly different arrangement of the earth's continents during the Cretaceous is now becoming sufficiently well known to geologists that a prediction of the poorly known climate and ocean circulation during that period should be carried out. A resulting improvement in the strategy for locating new oil reserves could have billion-dollar consequences in the field of energy production.

c. Regional/Process Models

These models are useful for understanding the interaction of selected physical processes in limited spatial and temporal domains. They give insight into certain aspects of local dynamics without the need for global or basin-wide equilibrium. Most of the reasons put forth in Section a as to the utility of EGCMs are equally valid for regional/process models. Examples of such models, which have already yielded substantial insights into ocean dynamics, are:

1. models of the local equilibrium of a mesoscale eddy field with bottom topography (Rhines, 1975, 1977; Bretherton and Haidvogel, 1976; Owens and Bretherton, 1978; Owens, 1979);
2. numerical models of oceanic jet instabilities (Cox, 1980; McWilliams and Chow, 1981);
3. open boundary forecast models (Robinson and Haidvogel, 1980);
4. models of Gulf Stream rings and solitary waves (McWilliams and Flierl, 1979);
5. models of the Indian Ocean seasonal cycle (Cox, 1976; Philander and Pacanowski, 1980);
6. equatorial models with simplified vertical structure Hurlburt et al., 1976; O'Brien et al., 1978; Cane, 1979; Gent and Semtner, 1980);

7. oceanic mixed layer models (Mellor and Durbin, 1975; Kim, 1976; Kraus, 1977; Garwood, 1979);

8. models of Gulf of Mexico (Hurlburt and Thompson, 1981).

9. Southern Ocean models.

Although regional/process models are somewhat less demanding than EGCMs and OGCMs in terms of computer time, there are nevertheless many groups using such models throughout the oceanographic community that feel computer limited to a significant extent. An improved effort in process modelling would have beneficial effects, not only for our understanding of local processes, but also for improving the treatment of these processes in EGCMs and OGCMs.

It should be noted that process models are really the only means we have for studying the full turbulent cascade of energy in the ocean, given that very high resolution can be employed. Horizontal grid spacings down to several kilometers are needed for such studies. It is likely that in certain modelling applications, the correct representation of the important turbulence process in strong current regions will require imbedding of high resolution, local models within larger-domain EGCMs or OGCMs. In this case, the computing requirement of the regional/process component of the model might exceed that of the model in which it was imbedded.

It must be stressed that process models have significantly improved the understanding of the local dynamical balances in many parts of the world ocean. They have also assisted in the optimal design of various oceanographic field programs (CUEA, POLYMODE, EPOCS, PEQUOD, and SEQUAL). They remain a primary link with the real ocean, in that they relate most closely to real time-series of data, including new types of data obtained by satellites.

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OCEAN MODELS FOR CLIMATE

The ocean plays many roles in the earth's climate system, almost all of which relate to the ocean's ability to store and transfer heat and to its exchange of heat with the overlying atmosphere. This coupling of the atmosphere and ocean is fundamental to the climate system, but is poorly understood because of the lack of adequate observations for the analysis of the highly non-linear processes involved. Moreover, changes in external forcing (e.g., insolation, anthropogenic effects, etc.) can disturb the balance of the climate system and require the establishment of a new equilibrium between the ocean and the atmosphere. It is only through the use of a variety of ocean models that the mechanics of ocean-atmosphere interaction can be discerned and an evaluation made of their role in the maintenance and change of climate on a variety of time scales.

On the monthly time scale, variations in the heat content of the oceanic surface mixed layer can lead to substantial sea-surface temperature (SST) anomalies, to which the atmosphere may in turn respond. On the longer time scales of seasons to years, there are large-scale variations of ocean circulation which may transport heat from one part of the ocean to another and thereby lead to local climate anomalies (e.g., El Niño). On the even longer time scales of decades and beyond, changes in air-sea interaction can lead to changes in the amount of sea ice and in the distribution of deep ocean water properties; these in turn can support new regimes of ocean circulation and SST patterns (e.g., Climap). In addition to their role in climate, such oceanic variations are important in the transport of essential nutrients for fisheries and in the transport and dispersion of man-made wastes in the ocean.

Our ability to study the coupled ocean-atmosphere system is today limited by the lack of knowledge on the physics of the boundary layers on either side of the air-sea interface, and by the inability to measure on a global basis the fluxes across this interface. We are also limited, however, by the unavailability of the computer resources required for the comprehensive modelling program which is required to examine the ocean's sensitivity to atmospheric changes and to develop adequate models of the ocean's role in climate.

Studies of the relevant ocean climate processes can be addressed with oceanic general circulation models by imposing climatological "surface" fluxes from the atmosphere similar to numerical experiments on the atmospheric effects of SST anomalies or CO_2 increases that have been carried out with atmospheric general circulation models. Important problems in such studies are understanding the formation and maintenance of the thermohaline circulation at different latitudes, the balance of deep water production by upwelling, and the forces controlling the abyssal circulation of the oceans. These processes are related to those responsible for the heat transport, CO_2 absorption, etc. on decadal and longer time scales, and evolve over hundreds of years before reaching equilibrium. It is therefore necessary to carry out extensive numerical integrations to study the long term climatic effects of changes in the forcing fluxes.

Because the details of mixing processes in the ocean are not well understood, it is also necessary to be able to perform sequences of model integrations in order to assess the relative performance of different physical parameterizations in the models. Further, careful consideration will have to be given to the possible effects of mesoscale motions in these models, as the degree to which these motions must be resolved by the model has great consequences for the computing resources required. Since the computing resources available for research in physical oceanography are presently severely limited, such calculations can now be carried out only in limited regions of the ocean.

Despite the limitations on our knowledge of many aspects of air-sea interaction as noted above, it is important to proceed with experimental calculations employing coupled ocean-atmospheric models. Even relatively simple versions of such models (e.g., those using an oceanic mixed layer) can be used to investigate the formation and evolution of SST anomalies. The possibilities for climate studies with more general coupled circulation models are limited at present by the scarcity of high-quality ocean and air-sea interaction data sets needed for verification, and by the overwhelming demands made on computational resources by this type of model.

Although considerable effort has been directed to the analysis of historical data sets and the collection of new oceanic surface data, our knowledge of surface wind stress, net surface heat flux and of the detailed thermal structure of the ocean on even the large scale is still quite limited. Greatly expanded data sets are needed to document the climate variability of the ocean and to support the development of improved models for climate research.

Improved modelling as well as expanded observational studies of sea-ice behavior is another area of great importance for climate studies in view of the large amount of heat that can be extracted by the atmosphere in polar and subpolar regions whenever leads occur in the ice cover. The extent of such leads depends on both the time history of the ice and the local surface pressure and wind stress fields, and requires a model for the salinity source provided by ice formation and melting.

It is clear that many climatologically important problems depend on our increased understanding of processes in the ocean. In order to address these problems adequately, improved data on the physical state of the oceans and the air-sea fluxes are needed to support significantly increased modelling activity for which greatly increased computational resources will be required. Only with the knowledge gained from such atmosphere-ocean model simulation experiments can we hope to obtain a better understanding of the behavior of the earth's climate system.

An extensive bibliography may be found in Ocean Models for Climate Research, U.S. Committee for GARP, NAS, 1981.

COASTAL DYNAMICS AND TIDES

The study of circulation and wave dynamics in the near coastal environment (including the continental shelf and slope) has received considerable attention by oceanographers in the last two decades for several reasons. One has been the renewed interest in coastal upwelling and its relation to all trophic levels of the rich biological communities within the coastal areas. Another is the concerns of the ecologists with regard to possible impacts of industrial pollutants introduced into the coastal environment, in which the redistribution by currents is a vital consideration. A third is the concern with real time prediction of flooding of coastal communities caused by severe storms crossing the continental shelf or by tsunamis generated by seismic events. A frontal attack on these and related problems of coastal dynamics has been made feasible by the emergence of the present generation of high speed computers and modelling technology. Moreover, some of the results of the modelling of wind-induced circulation on the continental shelf has led to such important discoveries as narrow undercurrents during upwelling events, which were later confirmed from high resolution field studies.

An excellent summary of the present state of the art regarding models of wind-driven currents on the continental shelf is given by Allen (1980). A related summary of recent advances in shelf wave dynamics is given by Mysak (1980). The efforts in numerical modelling of these phenomena has led to renewed interest in analytical aspects of the problems. Also, hand-in-hand with these studies have been advances in methods of analysis of current meter data as in the works of Allen and Kundu (1978), Brooks (1978), and Halpern (1976).

Models of wind-induced currents as employed in coastal upwelling studies are generally prognostic, n-layer, primitive equation models which allow for variable topography, rotation and variable wind input as in those of Hurlburt and Thompson (1973) and Peffley and O'Brien (1976). The latter models employ an efficient semi-implicit methodology which makes extensive parametric studies feasible.

Diagnostic models for quasi-steady circulational regimes in shelf regions have been developed by Hsueh and Peng (1978) and Galt (1980). These schemes, like their deep water counterparts, rely heavily on the existence of field data on density structure plus some information on boundary currents. They also rely heavily on appropriate "tuning" with respect to frictional parameters. They represent basically an objective method of interpolation and analysis of existing data so as to yield estimates of the circulation.

Models of storm-induced water level disturbances (surges) have been around for a long time. However, real-time prediction based upon the solution of the two-dimensional depth integrated equations of motion is relatively recent (Jelesnianski, 1965, 1972). Models which allow for coastal flooding have been employed in engineering design problems (Reid and Bodine, 1968; Butler, 1978). Models which allow for assessing the three-dimensional structure of storm generated currents in a homogeneous but viscous fluid have been applied by Forristall (1974, 1980).

A related problem is that of earthquake-induced tsunamis. Recent studies involving considerable computer effort in assessing the spectral response at island coastlines are reported by Bernard and Vastano (1977) and Houston (1978) for the Hawaiian Islands. The first of these studies employs a finite difference prognostic model with a broad-band spectral input (incident wave) in order to determine the excitation of trapped wave resonnances. The second study formulates the problem in terms of the forced helmholz equation for monochronatic waves and employs a finite element variational model to obtain numerical solutions.

While the modelling of tides is basically a global problem we have included a discussion of this in this section, because of its profound importance in coastal waters and because it represents primarily a barotropic forced wave problem. Also we would be remiss if we did not recognize the recent extensive modelling efforts which have been made in respect to this problem. Recent summaries of the subject are given by Hendershott (1977) and Schwiderski (1980). These serve not only to give a comprehension of the present state of the art in this longstanding problem, but also of the enormity of the computer efforts required in solving this on a global scale. It clearly can compete with OGCMs with respect to required computer resources, even if ADI or other implicit methods are employed in a time marching computation over a sufficient number of cycles to reach a steady forced state for a given tidal constituent.

A problem directly related to that of tides on a global scale, as well as to the barotropic model of response of the ocean to wind or pressure forcing at sub-inertial frequencies, is that of the barotropic normal model of the oceans. This problem has been addressed in three important papers by Platzman (1972, 1975, 1978). In the second two of these studies, both the gravity modes and the vorticity modes are investigated. The latter represent sub-inertial topographical planetary modes, which are important in circulational studies, while the gravity modes are more pertinent to the tidal problem or to surface forcing at super-inertial frequencies.

In each of the interesting and important problems discussed above (coastal upwelling, shelf waves, shelf circulation, coastal surges and tides), considerable progress with regard to predictive capability and understanding has been achieved through modelling efforts in concert with related field and analytic studies. However, there remains considerable room for further development. Most of the existing modelling studies have been accomplished with limited computer resources. In a way this has been good in that it has forced the modellers to proceed cautiously and has led to the development of fairly efficient algorithms for deriving the maximum information from limited resources. As in most pioneering studies with new tools, unforeseen areas of interest arise which need to be pursued. Such is the case with eddy resolving ocean models and high resolution shelf models in which the non-linear cascade of energy and dynamic instabilities need further study in order to point the way towards more adequate means of dealing with the turbulent closure problem at sub-grid scale. Indeed in the shelf problems where frictional boundary layers play a rather vital role in the quasi-steady circulation, higher order closure models such as those of Johns (1978) need to be pursued. However, these techniques can lead to a quantum jump in terms of required computer resources.

This is true as well of the global tidal and tsunami models which require better resolution in order to converge on solutions which are truly a simulation of the real world.

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