Scientific Justification For An Advanced Vector Computer

National Center for Atmospheric Research

Prepared for the National Science Foundation

University Corporation for Atmospheric Research
Boulder, Colorado

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Note: NCAR obtained a Cray XMP with 4-processors in Oct 1986. This test started the process.

Roy Jannas

Cover Illustrations:

At left are representations of transient ocean currents in the North Atlantic, derived from a numerical model of such flows. Much of the energy in the oceans is contained in the scale of eddy motions represented. The dark cross-hatched areas at left represent the Atlantic coastline from Florida to Newfoundland. Three depth layers are shown: From top, 0-300m; 300-1,000m; 1,000-5,000m.

At right, height-latitude sections of calculated and observed zonal wind averages are shown. These plots are outputs of the NCAR Community Climate Model, which is being used by scientific groups across the U.S.

Model outputs and plotting instructions were generated by the NCAR CRAY-1A computer and interpreted by the NCAR DICOMED graphics system, using NCAR-developed software.
# SCIENTIFIC JUSTIFICATION FOR
# AN ADVANCED VECTOR COMPUTER
# AT THE NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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EXECUTIVE SUMMARY

This report documents requirements of the nation's atmospheric scientists and physical oceanographers for a Class VII or Advanced Vector Computer (AVC). The computer will be used principally for research projects initiated by universities and non-profit research laboratories, and will be located at the National Center for Atmospheric Research (NCAR) at Boulder, Colorado. NCAR is operated by the 50-institution University Corporation for Atmospheric Research (UCAR) under the sponsorship of the National Science Foundation. The computer system will provide from one to two orders of magnitude greater high-speed memory and will be five to ten times faster than the CRAY-1A computer now operated by NCAR.

Development and use of complex mathematical models and massive data sets have become central to nearly every realm of atmospheric and ocean research. Progress in weather prediction theory, climate studies, severe storms research, ocean circulations, and the influences of the sun, land and oceans on the atmosphere all require such models and such data. As a result, university researchers have outstripped the computing resources now available.

Moreover, some of the most important problems in these fields of research have memory or computational requirements beyond the capabilities of the most powerful (Class VI) computers now available. Among such problems are realistic climate simulations, thunderstorm and tornado modeling, three-dimensional chemical-dynamical models, models of the solar cycle, turbulence modeling, and ocean general circulation models with the dynamics of mesoscale eddies taken fully into account.

Hence progress in research useful in attacking such problems as acid rain, global air quality, climatic change, warnings to protect life and property, and predictions that promote efficiency of transportation and commerce is now seriously impeded by the lack of adequate computing resources. Public interest in these questions is evidenced by the National Climate Program Act and by recent Congressional hearings on climate prediction, acid rain, aircraft safety, and severe storm warnings, and by widespread national media attention to these and other subjects.

This report discusses in some detail the problems that require the speed and memory of a Class VII machine. The aggregate requirement for computing resources in the mid-1980's will be the equivalent of seven to nine CRAY-1As. Such a machine will provide significantly higher power-to-cost efficiency. Current estimates indicate a factor-of-five improvement compared to the power-to-cost ratio of the CRAY-1A.

NCAR has for 20 years pioneered in supplying new, powerful computers and software, along with a full range of computing services, to the university-based atmospheric research community, and to a significant number of scientists
yrom physical oceanography, solar physics, and related disciplines. Many significant scientific achievements (described in Chapter II) have resulted from use of the NCAR facility, which now serves more than 800 individual users each year, many of them using remote-access devices in more than 75 locations around the country. It is envisaged that the Class VII computing system will be used remotely through satellite links as well as by land-based methods.

A small percentage of the current NCAR computer resource is now used by physical oceanographers. UCAR proposes that when the AVC begins operations, the NCAR facility then will be a major national computing resource for physical oceanography.

The NCAR facility is the only major computing center in the U.S. fully dedicated to the atmospheric sciences and closely related fields where university scientists have first-priority access. A time-tested allocation system, monitored by the community itself, ensures access based on merit alone. NCAR's hardware and software systems and specialized user services, including a full complement of archival and analytical tools, provide an efficient, full-service facility for the community.

The scientific community has participated broadly in assigning high priority of acquisition of a Class VII system for operation at NCAR. The basic scientific justification was developed by nationally known scientists from NCAR and eleven other institutions. In response to a widely-circulated letter-questionnaire, the opinions of more than 200 scientists across the country were received. There has been extensive discussion and endorsement by user conferences, the Advisory Committee to the NCAR Scientific Computing Division, and the UCAR Board of Trustees.

Management and allocation of the resources of the Class VII system will be based on processes now in place, with appropriate adjustments to handle a greater computing load and a broader user base.

Cost of the Class VII system, including essential peripherals, is expected to be $20 million. Financing options are discussed in Chapter V. A mass storage system required for continued effective operation of the NCAR system will cost an additional $3 million. Installation of the AVC is estimated to cost $1.4 million, including a 1,400-square-foot addition for expansion of mechanical space. Thus total capital costs are estimated at $24.4 million. Operating costs for the Class VII computer, the mass storage system and associated peripherals will add approximately $1.9 million to the annual cost of operating the NCAR facility.

UCAR requests that the National Science Foundation provide sufficient funding for acquisition of the Class VII computer and mass storage system in FY 1985. The systems would then go on line in the summer of 1986.
CHAPTER I

INTRODUCTION AND SUMMARY JUSTIFICATION

The development and use of complex mathematical models have become increasingly important means of integrating and extending our knowledge of many important aspects of the atmosphere and of physical oceanography, including related chemical and biological aspects. Such models were first developed as tools to analyze and understand large-scale motions, and thus to provide a new foundation for improved weather prediction. In the past decade, however, a broad spectrum of large models has been developed to probe the many complex phenomena occurring in the atmosphere and oceans and how they interact to produce significant end results. These models are at the heart of many areas of research, including climate and climatic change, atmospheric chemistry (including acid rain), ocean dynamics, the interaction between the oceans and the atmosphere, the formation of clouds and severe local storms, the theory of turbulence, and the relationship between solar events and the earth's atmosphere.

Very large computers are now essential to the study of the dynamical, chemical and physical aspects of the atmosphere and its interactions with the ocean, the land, and the sun. The nature of atmospheric and oceanic science makes the amount of available computing speed and memory a critical limiting factor in how well and rapidly knowledge can be generated and applied. A major part of the current global effort in atmospheric and oceanic modeling is carried out at American universities and at NCAR. These activities are now served by NCAR's Scientific Computing Division. While the current evolution of mini-computers and larger "midi" machines is putting more computing power at the disposal of scientists at their home institutions, a central facility, with a full complement of archival and analytical graphics tools and user services, is an essential component of an effective national research effort. It is the experience of most workers that the availability of larger machines on their home ground increases the effectiveness with which they can use the largest machines to attack the central modeling problems of the atmospheric and ocean sciences.

The advent in the 1970's of the Class VI machine (e.g., the CRAY-1 and the Control Data CYBER 205) allowed atmospheric and oceanic research to make significant advances across a broad front. Many of these advances are described in Chapter II. Similar advances in the 1980's will be possible only through the use of a Class VII or Advanced Vector Computer (the terms are used interchangeably in this document).

Summary Justification

The Advanced Vector Computer (AVC) should be placed at the National Center for Atmospheric Research (NCAR), in Boulder, Colorado, which is operated by the 50-institution University Corporation for Atmospheric Research under the sponsorship of the National Science Foundation. Such a computer will provide five to ten times the present computing capability of NCAR's CRAY-1A system, as well as high-speed access to a central memory sufficient to handle the large amounts of data used and generated by mathematical modeling studies.
Justification for the AVC at NCAR is based on three principal factors. The computer is essential for continuing progress in the atmospheric and oceanic sciences. The scientific research to be done is important, both intellectually and from the standpoint of public interest. NCAR is the most logical place for the computer: NCAR has a record of pioneering computing service to the university community; much of the requisite research in atmospheric and ocean sciences is being done at universities; NCAR's sponsor, the National Science Foundation, is dedicated to the national health of fundamental research, particularly in the universities.

Chapter II, with six sections drafted by nationally recognized leaders in their subdisciplines, demonstrates the intellectual and practical importance of the research to be done. It shows the extent to which the lack of sufficient large-scale computing resources places a major obstacle in the way of progress in research. Requirements for the equivalent power of seven to nine CRAY-1A computers by the mid-1980's are described.

The NCAR facility, the only major facility totally dedicated to atmospheric and ocean science and open to all university scientists, now has the equivalent of 1.2 CRAY-1As, and replacement of NCAR's current CDC 7600 in 1983 will increase this power only to about 1.8 CRAY-1As. Even when several Class VI machines at universities and elsewhere become partially available to the atmospheric sciences community at large, it is likely that not more than a minor fraction of the mid-decade need will be met by this combination of machines.

Moreover, many critical problems in atmospheric and ocean research require so much speed and memory that they cannot be efficiently run on a Class VI machine. As discussed in Chapter II, these problems include more realistic climate simulations, tornado modeling, advanced model to predict storm-scale precipitation, coupled three-dimensional chemical-dynamical models, thermosphere-ionosphere interactions, growth and evolution of sunspots, realistic models of ocean circulations, and fully dynamic models of ocean-atmosphere interactions. The speed of Class VI computers is such that unrealistically long runs would be required to attack such problems, and requirements for memory far outstrip the capacity of Class VI machines.

Community opinion, according to a survey conducted in 1982 and reported in Chapter III, supports the conclusions of the nationally-acknowledged scientists who co-authored Chapter II. Widespread support for a Class VII machine is evidenced by this survey.

The history of NCAR's computing capability and service, described in Chapter IV, demonstrates that NCAR is an optimum location for the AVC. NCAR has had two decades of pioneering in providing computing support to universities. An effective array of modes of communications and services assists scientists in time-efficient use of NCAR's computing power, including remote use from their home campuses.

As discussed in Chapter V, the NCAR computing center is the only such facility devoted entirely to serving the university atmospheric sciences and physical oceanographic community. There is a tested and accepted method of resource allocation to the community. NCAR performance and plans are reviewed
frequently by the UCAR Board of Trustees, by an Advisory Panel, by independent reviewers representing the university community, and by user conferences.

Plans for acquisition of the AVC are embedded in an overall plan for the development of the NCAR facility, as described in Chapter V, in order to ensure the most effective use of the AVC. Management and cost considerations are also covered in Chapter V.

The computing power made available to the scientific community by NCAR has increased approximately five-fold every seven years since the facility was established. Each increase has made possible scientific advances not previously possible. Each increase in power has been promptly and efficiently made available by NCAR, and quickly and effectively used by the research community. The many specific scientific advances that involved use of the CRAY-1A at NCAR are discussed in Chapters II and III.

The importance of atmospheric and ocean research to public concerns (industry, agriculture, air and sea transport, environmental affairs, and protection of life and property) is exemplified by the interest expressed in atmospheric research over the past few years by the U.S. Congress. In 1978, the Congress passed the National Climate Program Act to spur research on potential climate changes that could occur, affect world food and energy strategies, and on the effect of human activities on climate. Numerous congressional inquiries have been conducted to assess the state of knowledge in atmospheric chemistry (particularly acid rain), the effects of fluorocarbons and other substances on the stratospheric ozone layer, the climatic effects of increasing worldwide carbon dioxide, and environmental concerns affecting the oceans. The Congress has also actively inquired into how research and technology can promote the improvement of warnings of severe weather, such as tornadoes, downbursts and wind shear events that threaten aircraft, hurricanes, blizzards, and severe heat and cold.

A National Academy of Sciences study, The Atmospheric Sciences: National Objectives for the 1980's (National Academy of Sciences, 1980), identifies three areas where there are special opportunities for research progress of greatest interest to the nation: weather prediction, climate, and atmospheric chemistry. The need for additional major computer resources was underlined in this report, as well as in other recent reports, including the 1981 report of the National Advisory Committee on Oceans and Atmosphere, A Review of Atmospheric Research Facilities; the 1982 Academy report, An Assessment of Computational Requirements for Ocean Circulation Modelling; and the 1981 report of the Academy's U.S. Committee for the Global Atmospheric Research Program, entitled Ocean Models for Climate Research. All of these reports conclude that only through the availability of greatly augmented computing capabilities will many of the most significant and useful advances in the atmospheric and ocean sciences be attained.

University Computing Capabilities Taken Into Account

Planning for the acquisition of the AVC at NCAR is being carried out in the context of an important evolution of computing resources at universities. In the past two years, several universities and other institutions have
acquired, or have announced plans to acquire, Class VI computers (CRAY-1As, CDC CYBER 205s). A modest amount of software is available with these systems, and these capabilities will be available to scientists from other institutions on a variety of bases. Other universities have also upgraded their computing capabilities on more modest scales. In deciding that an AVC should be acquired by NCAR, UCAR has taken the following factors into account:

1. Power-to-cost efficiency. By 1984, the next generation of high-speed computers will be available, with increased speeds of at least five times. As in each previous generation of computers, there will be a marked increase in the power-to-cost ratio. For work requiring Class IV- or-better capability, as described in Chapter II, the efficiency of a Class VII machine will be substantially better than Class VI machines operated for the wide variety of purposes characteristic of university computing centers. Table 1 presents approximate power-to-cost ratios for various types of computers.

2. Services required. The total spectrum of services required by scientists engaged in large-scale atmospheric research computing must be taken into account. Not only is the work computer-intensive, but hierarchical storage, graphics support, data archives, and communications must be provided in extremely large quantities. Many research projects such as those described in this document use a large fraction of these resources intensively but only for brief periods. It is unlikely, therefore, that individual institutions will develop, or can afford to develop, a configuration of general service that can accommodate essential requirements of large-scale computing projects. The requisite services can be most effectively and efficiently provided by a computer center used by many atmospheric and ocean scientists from many institutions. Moreover, the NCAR Scientific Computing Division has made significant contributions to software and algorithm development that have benefitted the atmospheric sciences, oceanography and other fields.

3. Meeting the needs of major modeling experiments. As previously stated, and as discussed in detail in Chapter II, many of the most important groups of experiments will consume significant fractions of the capacity of a CRAY-1A-class computer, and some are so extensive that they cannot be run except on a Class VII machine.

Consultation Within the Scientific Community

The identification by UCAR of a Class VII computer and essential peripherals as the highest-priority single major facility for university-based atmospheric science in the 1980s has been reached after extensive consultation with the large community that uses NCAR computing facilities, as well as with an even larger number of scientists in the broader science community.

The broadest such consultation, a survey letter sent to more than 800 members of that community, was conducted earlier this year. As reported in Chapter III, responses representing more than 200 scientists were received by NCAR. These responses strongly support the proposition that a Class VII computer is essential to significant progress on many problems of the greatest scientific and public interest.
Table 1

COMPARISON OF ESTIMATED COSTS OF COMPUTING ON MACHINES OF VARIOUS SIZES
(Based on speed comparisons with a CDC 7600)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Cost per Wall Hour (assumes 8,000 hr./yr. operation)</th>
<th>Cost per Equivalent CDC 7600 CPU Hour (assumes CPU is active 70% of time)</th>
</tr>
</thead>
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<tr>
<td>CYBER 170/720 (Speed=0.1\times 7600), (b)</td>
<td>525k</td>
<td>$15</td>
</tr>
<tr>
<td>Tape drives and disks</td>
<td>675k</td>
<td>33</td>
</tr>
<tr>
<td>Maintenance</td>
<td>100k/yr.</td>
<td>13</td>
</tr>
<tr>
<td>CYBER 176 (Speed=1.2\times 7600), with 500k word memory</td>
<td>5,100k</td>
<td>140</td>
</tr>
<tr>
<td>Tape drives and disks</td>
<td>1,000k</td>
<td>28</td>
</tr>
<tr>
<td>Maintenance</td>
<td>250k/yr.</td>
<td>31</td>
</tr>
<tr>
<td>CRAY 1A (Speed=4.5\times 7600), with 1,000k word memory</td>
<td>7,200k</td>
<td>198</td>
</tr>
<tr>
<td>Tape drives and disks</td>
<td>1,300k</td>
<td>36</td>
</tr>
<tr>
<td>Maintenance</td>
<td>400k/yr.</td>
<td>50</td>
</tr>
<tr>
<td>AVC Computer (Speed=34\times 7600), with ~4,000k words &amp; disks</td>
<td>20,000k</td>
<td>550</td>
</tr>
<tr>
<td>Maintenance</td>
<td>500k/yr.</td>
<td>63</td>
</tr>
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PERSONNEL COSTS (Loaded)(c)

| CYBER 170/720 (3 operators, 2 programmers, 1 manager) | 215k/yr. | 27 |
| CYBER 176 (25 operators, 20 programmers, management) | 1,700k/yr. | 212 |
| CRAY 1A (30 operators, 25 programmers, management) | 2,100k/yr. | 262 |
| AVC Computer (same as CRAY 1A) | 2,100k/yr. | 262 |

(a) Approximate costs valid in 1981, except for the AVC computer, not yet announced. Annual cost of capital investment is assumed to be 22%.
(b) Relative speeds and 70% CPU utilization assumes a mix of jobs similar to that now performed by the NCAR CRAY-1A.
(c) Assumes each machine is the only one at the operating institution.
In January 1981, the NCAR Computer Users' Conference, concentrating on computer planning for the 1980s, placed the "provision of computer capacity adequate to the needs of the atmospheric science community" as the first priority in expansion of computer capabilities. The conference, attended by 40 major users from 26 institutions, represented nearly every atmospheric discipline that develops models and exploits very large data sets. The acquisition of computing capability equivalent to five Cray-1As was identified as being the first priority in time as well as in importance. A list of participants at this conference is given in Appendix A. Statements concerning the computing needs in the various subdisciplines represented are reproduced in Appendix B.

The Advisory Panel to the NCAR Scientific Computing Division, a group composed primarily of non-NCAR scientists that reviews long-range strategies for the division, also assigned highest and most urgent priority to the AVC. Formal actions occurred at Panel meetings in April and October 1981, and March 1982, urging UCAR to move as quickly as feasible to acquire the AVC. Panel membership is given in Appendix C.

At its September 1982 meeting, the Panel commented:

"The Advisory Panel...believes that the acquisition of such a computer is essential to the continued advancement of research in the atmospheric and related sciences...NCAR has served and serves as a premier source of computational support...An extensive and important set of atmospheric and related science issues can be pursued by university and NCAR researchers only with the installation of such a system at NCAR... The Panel views the installation of an AVC as the highest priority..."

The full text of the Panel's statement is contained in Appendix D-1. An April 1982 statement by the Panel, Appendix D-2, addresses both the current overload on NCAR computing resources and long-term future needs.

The UCAR Board of Trustees has endorsed the assignment of highest priority among proposed major capital acquisitions planned for NCAR in the next several years. (Names of the UCAR Trustees appear in the front material of this report.) At its October 1982 meeting, the UCAR Board of Trustees reiterated its position on the AVC, stating that "certain important advances in atmospheric and related research depend on major augmentation of current computing capabilities" and said the acquisition of the AVC holds "highest priority among larger capital acquisitions" for NCAR.
CHAPTER II

MAJOR SCIENTIFIC REQUIREMENTS FOR AN ADVANCED VECTOR COMPUTER

There are six major areas of atmospheric research that require intensive use of large computer facilities. UCAR has asked a leading scientist in each of these fields, in consultation with one or more colleagues, to describe the progress that has been accomplished on the CRAY-1A computer, the major problems for the 1980s that require sizable computer resources, and the amount of computing resource required to attack the problems discussed. The authors have concentrated on the largest and most critical problems in each area.

The following table summarizes requirements to treat adequately the problems discussed in this chapter:

<table>
<thead>
<tr>
<th>Area of Research</th>
<th>Requirements for Large-Scale Computing Projects (in CRAY-1A units)</th>
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<tr>
<td>Mesoscale Dynamics</td>
<td>0.7</td>
</tr>
<tr>
<td>Climate Research</td>
<td>1.5 to 2.2</td>
</tr>
<tr>
<td>Atmospheric Chemistry</td>
<td>1.2 to 1.4</td>
</tr>
<tr>
<td>Oceanography</td>
<td>1.0</td>
</tr>
<tr>
<td>Solar Fluid Dynamics</td>
<td>0.6</td>
</tr>
<tr>
<td>Turbulence Research</td>
<td>0.8</td>
</tr>
</tbody>
</table>

TOTAL REQUIRED FOR MAJOR PROJECTS 5.8 to 6.7

In addition to this total, from one to two additional CRAY-1A units will be required for work on other problems across the spectrum of the atmospheric sciences. Hence the total large-scale computing requirement in the mid-1980’s is estimated to be from 7 to 8.5 CRAY-1A equivalents.

A further critical need, discussed in this chapter, is for far larger memory than Class VI computers provide. The AVC will meet this requirement.

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A CRAY-1A unit is 6,000 hours per year of CPU time, based on a ratio of .7 for CPU time/wall clock time.
MESOSCALE ATMOSPHERIC DYNAMICS

(Drafted by Richard Anthes, NCAR, in consultation with William Cotton and Roger Pielke, Colorado State University, and Douglas Lilly, University of Oklahoma)

The mesoscale, commonly thought of as extending from a kilometer to about 2,500 km in horizontal dimensions, is the scale on which the public most frequently experiences weather. Hurricanes, tornadoes, rain and snow squalls, high winds, hail, and air pollution events are all mesoscale events. Moreover, when a larger synoptic-scale event occurs (such as the formation of a large low-pressure center as seen on weather maps), the ice storms, thunderstorms, heavy rains, and other events that people must react to are modulated by local and regional mesoscale processes.

Until the recent advent of sophisticated measuring systems (Doppler radars, specialized ground networks, instrumented aircraft) and high-speed computers, advances in mesoscale research and in applying those advances to operational forecasts were slow in coming. In the past several years, however, our knowledge of the mesoscale has advanced rapidly. Theory, observational technology, and computer methods are now ready to accelerate progress and to yield applications that will enhance our ability to issue forecasts and warnings of use in protecting life and property and in increasing the economic efficiency of various areas of transportation, commerce, and agriculture.

The research discussed in this section is directly related to the priority research agenda set down in the National Academy of Sciences 1980 publication, "The Atmospheric Sciences: National Objectives for the 1980's." This document identified six research objectives in the areas of weather prediction, atmospheric chemistry, and climate research that combine these crucial characteristics:

- A research community that is scientifically ready to pursue them in a coherent manner
- A required technology already developed or in sight
- A clear connection to urgent national problems.

Among the six objectives were improvement of local short-range prediction methods and cyclone and frontal-scale prediction, with emphasis on the prediction of precipitation and severe weather. These are the major ultimate practical products of mesoscale research, and thus constitute a major justification for the computing resources required for an effective overall mesoscale research effort.

Classification of Mesoscale Models

Since the term mesoscale covers a wide range of scales, and many meteorological phenomena belong, at least in part, in the mesoscale, we have classified models of the mesoscale into three types, corresponding
approximately to Orlanski's classification: Meso-α (horizontal scales from 250 to 2,500 km), meso-β (horizontal scales from 25 to 250 km) and meso-γ (horizontal scales from 2.5 to 25 km). The typical grid size for a meso-α scale model is about 50 to 200 km; for a meso-β scale model 5 to 50 km, and for a meso-γ scale model less than 5 km. The differences among these models are emphasized first in this discussion, but we will also discuss their commonality.

Meso-α scale models are typically used for predictions initialized with real data (as contrasted with model-generated or simulated data) over regional or continental scales for time periods of 0-48 h. With the current Class VI computers, it is feasible to utilize these models operationally. Such meso-α scale models may be viewed as descendants from the synoptic-scale models of the 1960s, the major difference being an increase in horizontal and vertical resolution. A major emphasis in the refinement of meso-α scale models has been in the development of improved physical parameterizations such as the representation of boundary-layer or cumulus convection effects. Meso-α scale models have shown great potential in predicting such phenomena as low-level jets, frontogenesis, drylines, mesoscale convective complexes, and orographic precipitation.

Meso-β scale models have emphasized the simulation of atmospheric phenomena to increase fundamental understanding rather than to make predictions with real data. Notable progress in simulating land-sea breezes, orographic flows, frontal circulations, tropical cyclones, and coastal fronts has been made in recent years utilizing meso-β scale models.

Most meso-γ scale (cloud-scale) models thus far developed have emphasized the simulation of convective clouds and severe thunderstorms. Cloud-scale models involve many physical processes taking place on scales smaller than the meso-γ scale but which influence precipitation and dynamic processes on the γ scale. In addition, some of the models treat electrical, chemical, and radiative processes that may influence mesoscale phenomena, such as thunderstorms, acid rain, and stratus-filled atmospheric layers.

As opposed to larger-scale models, cloud-scale models attempt to simulate the details of precipitation evolution and air motion over grid intervals of a few hundred meters (or less) to 1 km, and over domains a few kilometers on a side to several tens of kilometers on a side. Atmospheric depths up to 20 km are often modeled, and the models and generally nonhydrostatic. Cloud models in one, two, and three space dimensions and either time-dependent or steady-state are being used in various aspects of cloud physics research, in prediction, and in assessing the potential impacts of intentional and inadvertent modification. The simpler one-dimensional cloud models are coupled with some mesoscale models to yield predictions of precipitation on the mesoscale. The more dynamically complex three-dimensional cloud models simulate many of the characteristics of severe local storms, including tornadoes.

Cloud-scale models vary in both microphysical and dynamic complexity. Simple, highly parameterized microphysical models require
one-tenth detailed particle-spectra modeling methods. More microphysical complexity is added as cloud electrification, cloud chemistry, and cloud radiative processes are included in the models. In addition, the treatment of both ice and liquid phases in clouds, necessary for snow and hail prediction (and for predicting rain in highly convective situations), makes the cloud models more complicated and requires more computer power for their solution. The two-dimensional cloud models are now being used most often to attack these cloud-physics problems.

Notwithstanding the great variety of mesoscale weather phenomena (e.g., hurricanes, severe thunderstorms, tornadoes, ice storms, flash floods, damaging downslope winds, fog, and low cloudiness), all such mesoscale phenomena may, in principle, be modeled with general models based on approximately ten prognostic equations. Thus, models with rather similar basic characteristics have been by university and NCAR scientists used over the past five years at the NCAR computing facility to simulate the following phenomena:

- flow around individual hills
- mountain waves
- orographic precipitation
- air quality simulations
- mountain-valley breezes
- sea breezes
- severe thunderstorms
- mesoscale structures embedded in extratropical cyclones
- tropical cyclones
- frontal circulations
- squall lines
- tornadoes
- mesoscale convective complexes
- dry lines
- jet streak circulations
- coastal effects
- rainbands
- urban circulations

Computer Requirements of Mesoscale Models Thus Far Developed and in Prospect

Three-dimensional mesoscale modeling requires spatial arrays of at least 10 x 40 x 40 (i.e., 16,000 grid points) in order to produce credible results. With at least six different variables required at each grid point (e.g., three velocity components, temperature, pressure, humidity) at two time levels, plus a number of two-dimensional arrays.

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3 A fuller discussion of progress in modeling these phenomena is presented in the planning documents: The National STORM Program—Scientific and Technological Bases (UCAR, November 1982), and the National STORM Program—Framework for a Plan (UCAR, October 1982).
e.g., for terrain elevation, roughness length), a core requirement of over 200,000 words is needed for a relatively simple three-dimensional calculation. Calculation times for the above formulation would require about 2.5 h of CRAY-1A time for a 24-h calculation with a horizontal grid increment of 5 km.

More realistic three-dimensional simulations require substantially larger arrays and hence strain the capabilities of the CRAY-1A. Only a very limited number of model sensitivity runs can now be performed on CRAY-1A class machines. Yet, representation of most of the essential physics of mesoscale phenomena requires three dimensions.

The NCAR computing facility is unique in its dedication to basic research in the atmospheric sciences in the university community. Although competition for resources among investigators and fields of atmospheric research is becoming severe, several groups have made great progress in mesoscale research using the CRAY-1A at NCAR (Table 2). A conservative estimate is that these groups have collectively published over 200 papers in the reviewed literature and produced more than 40 Ph.D. theses in the past five years. These papers involved in part, or in their entirety, three-dimensional simulations of mesoscale systems in actual geographic areas, as well as many idealized theoretical experiments. This effort could not have been done without a CRAY-1A-class computer.

The following section summarizes recent progress involving 3-D models as one example of progress in mesoscale meteorology. Similar progress in understanding other mesoscale phenomena are discussed in the STORM planning document (see footnote, previous page).

Interactions of Cloud and Storm Modeling and Observational Studies

With the availability of advanced computers of the capability of the NCAR CRAY-1A, three-dimensional cloud or storm models have become the most effective means of understanding the processes contributing to the formation of tornado-producing meso-cyclones; the propagation of convective storms; the factors contributing to splitting of thunderstorms into two separate storms; the role of mesoscale convergence in regulating convective cloud intensity, rainfall, hailfall, and wind; and for examining the potential for modeling convective clouds and storms by cloud-seeding techniques. Because of their realistic replication of certain observed features of convective clouds, three-dimensional models have also become a powerful tool in the analysis and interpretation of observed cloud phenomena. Thus, in the last five years, we have seen the parallel rise of major observing systems of convective storms including multiple Doppler radar, automated remote ground-based in situ observing networks, sophisticated airborne observational platforms and three-dimensional cloud models. The insights provided by the cloud models have had a major impact upon the interpretation and synthesis of the vast quantities of data that are produced by these observing systems, as well as for the identification of measurements most needed.

The first successful simulations of convective storms in a strongly sheared environment that showed rotational evolution were made by Klemp
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and Wilhelmson and by Schlesinger in 1977, both using and straining the NCAR CDC 7600 computer. The early availability of the CRAY-1A, together with strikingly significant early results, encouraged rapid development of the field. As the observational community began to take note of the rapid conceptual changes stimulated by the early rotating storm simulation, analyses of multiple-Doppler records of severe storms events were made; these in turn stimulated new model studies aimed at investigating the important small-scale features leading to tornado formation and evolution. Limitations on computer speed and memory, and competition with other researchers has become more severe, but progress has continued through use of nested-mesh modeling and other kinds of compromises.

However, the current limitations on computer power at NCAR are now beginning to produce some deceleration. This is occurring at a time when the observational and theoretical communities are reaching new levels in productive interaction.

An example of the kind of creative observational work being pursued in convective and small-scale dynamics is the effort by Gal-Chen, Hane, Kropfli, and others to show the feasibility of recovering the thermodynamic fields (pressure and buoyancy mainly) from multiple Doppler velocity data. With the aid of a specially designed boundary-layer numerical experiment, it has now been found that convective heat flux profiles can be plausibly estimated over a representative volume. These profiles are an important indication of the high potential accuracy of Doppler techniques.

This work can be considered a prototype of a more sophisticated utilization of remote-sensing instrumentation than had previously been attained, and has great potential for practical application. It is highly computer-intensive. Each radar scan sequence, repeated in about 4 min of real time, produces about $2 \times 10^5$ velocity determinations from each radar within the sample volume, all of which must be massaged and combined in various ways to produce the end product.

A growing use of convective storm simulations is in the prediction of potential storm intensity and structure from real or predicted environmental soundings. While the operational utilization of simulation models for predicting the evolution of storms is still not yet clearly in sight, it is likely that the simulation of prototype storms from real data will eventually be of operational value. An operational system may be such that a forecaster can determine the type and intensity of the storm by reference to standard tables well in advance of the occurrence of the storm, or it may be more effective to use statistical techniques in real time. It is too early to tell. Research in these directions is being pursued at NCAR and should be accelerated in the future, but it is now clearly limited by computing power and memory limitations.
Important Problems to be Attacked During Next Five to Eight Years

Recent national deliberations about the potential of mesoscale meteorology have resulted in the identification of five major objectives for the next decade. These objectives are of great scientific interest and have the potential of contributing to the improvement of weather services to the public. To pursue these objectives effectively, both major theoretical work and extensive field experiments are necessary. This section describes the kinds of mesoscale research that will be carried out in the coming years, in order to serve as a basis for estimating future computational requirements.

(1) Description and understanding of scale interactions. To determine and quantify how scales of motion interact, ranging from the synoptic scale to the meso-γ scale, the following activities are required:

- Describe structure of mesoscale phenomena
- Describe mesoscale fluxes of heat, moisture, and momentum for developing better physical parameterizations of small-scale atmospheric processes
- Study the physical and dynamical effects of deep and shallow cumulus convection on meso-α and synoptic scales
- Determine the magnitude and mechanisms for transfer of energy upscale and downscale under various synoptic and mesoscale conditions

(2) Predictability and prediction. To achieve greatly improved prediction of mesoscale weather phenomena, the following major activities are required:

- Define new measures of predictability of mesoscale phenomena, and study theoretically and through numerical modeling the limits of mesoscale predictability
- Establish the current level of prediction capability and its usefulness
- Develop new methods for predicting mesoscale phenomena from larger-scale fields
- Establish the relative contributions of forcing by inhomogeneities at the earth's surface and of scale interactions associated with motions in the atmosphere in creating mesoscale circulations.

A national agenda of mesoscale research in the next decade has been generated for the National STORM Program (See Footnote 2, Page II-4).
(3) Prediction of precipitation. Included under this heading are the subobjectives of improving understanding and capabilities to predict precipitation, including precipitation over mountains, all types of frozen precipitation, and heavy rains that produce flash floods; determining the relationship of mesoscale systems to larger scales of motion; determining the scientific basis for weather modification, intentional and inadvertent; and the dynamical mechanisms involved in the formation of acid precipitation. To pursue this overall objective, the following activities are required:

- Determine more effective ways of using remote-sensing systems (e.g., satellites, radars) to detect and observe precipitation through its life cycle
- Examine effects of topographic and land-use variations on precipitation patterns and amounts
- Relate the planetary boundary-layer structure to formation, maintenance and decay of mesoscale precipitation systems
- Determine influence of meso-β scale environment (stability, water vapor stratification, wind shear) on precipitation systems
- Determine the physical mechanisms responsible for generating, maintaining, and dissipating severe convective precipitation storms
- Determine the respective influences of meso-α and meso-β scale phenomena (e.g., upper-level jet, low-level jet, isallobaric winds) on precipitation systems
- Determine mechanisms of cloud electrification and relation to microphysical processes.

(4) Development and testing of mesoscale models. To develop and test improved numerical models of mesoscale phenomena in order to carry out controlled simulations and to improve operational predictions. To pursue this objective, the following activities are required:

- Develop and verify improved parameterization of subgridscale physical processes, such as condensation, radiation, and planetary boundary-layer fluxes
- Determine the limits of predictability using deterministic models
- Identify through the use of models the large-scale environmental parameters associated with smaller-scale significant weather
- Determine the impact of new data sources (e.g., asynoptic satellite or radar data, rainfall rate data) and alternative sampling densities (spatial and temporal) on forecast accuracy
• Develop improved ways of initializing numerical models to accommodate new sources of data in consistent, dynamical ways (e.g., develop analogs to the normal mode method for global models).

(5) Observing systems tests. To design, develop, and test improved observing systems and to provide comprehensive data for use in research and operations. The following activities will aid in pursuit of this objective:

• Develop total observing systems on all mesoscales, using soundings, Doppler radar, aircraft, and ground observations to measure the parameters essential for defining mesoscale phenomena.

• Develop and test methods for using satellite data combined with ground-based sensors to produce mesoscale analyses of winds, temperature, water vapor, clouds, and precipitation.

• Determine the extent to which special observational systems (such as airplanes) can make measurements in critical regions of the atmosphere (such as jets, moist tongues, frontal zones) and determine how such measurements can improve understanding and prediction.

• Develop and compare objective analysis schemes through actual forecast tests and by other means.

Computing Resources Needed to Attack Problems in Mesoscale Meteorology

Estimates of Computer Time Required

The current mesoscale research being carried out by NCAR, university, and government scientists is directed principally toward a more complete description and understanding of the evolution of the critical elements of mesoscale phenomena, particularly those involving severe weather, such as tornadoes, intense downdrafts, extreme precipitation, and hail. Since the scales of these phenomena span several orders of magnitude, they cannot be simultaneously resolved in simulations using a CRAY-1A class computer. The use of nested mesh techniques has allowed simulation of some significant small-scale structures embedded within larger-scale circulations. However, even with nested grid models, only a portion of the storm can be included within the high-resolution domain, and the model can only be integrated for a few minutes before boundary influences corrupt the solution. The results from this area of research thus far are only a prelude to the knowledge that can be produced with Class VII computing capabilities.

Storm initiation and regeneration processes are other important topics which are not likely to be well investigated through numerical modeling without the benefit of next-generation computer technology. The
important scales of motion during the initiation of convection are much smaller than those of the developed storm and require significantly improved grid resolution (requiring both enhanced computer speed and memory) to be viably simulated. Enhanced computer capabilities will also be required to investigate adequately the interactions between storms and their larger-scale environments. Both the mesoscale forcing of thunderstorms and the feedback of their momentum and energy exchanges to the environment occur on scales larger than the size of the current model domain. Bridging the gap between the larger mesoscale and the cloud scale is thus likely to require considerable increase in domain sizes without substantial reduction in grid size.

The following are estimates of the requirements of the university-NCAR community's work in mesoscale research for the remainder of this decade. They are given in CRAY-1A hours (CH) and are based on the number of groups now planning to be active and the average computer resource each group is likely to require:

(1) Severe weather: requires higher-resolution, meshed models from meso-α to tornado scale, detailed microphysics for hail and lightning; total number of groups - 6 @ 20 CH/month
   CH per year = 1,440

(2) Weather modification potential (intentional and inadvertent): models of cloud microphysics and dynamics, cloud scale to meso-α; total number of groups - 6 @ 5 CH/month
   CH per year = 360

(3) Meso-β scale simulations and meso-α to meso-γ scale interactions: requires at least a doubling of horizontal resolution and more general treatment of condensation and evaporation processes; total number of groups - 3 @ 20 CH/month
   CH per year = 720

(4) Radiation/cloud turbulence/precipitation/mesoscale interactions: total number of groups - 2 @ 5 CH/month
   CH per year = 120

(5) Field data interpretation: primarily meso-γ and cloud microphysics; total number of groups - 4 @ 5 CH/month
   CH per year = 240

(6) Formulate parameterizations: mostly diagnostic analyses of model experiments listed above; total number of groups - 5 @ 5 CH/month
   CH per year = 300

(7) Precipitation chemistry: generally involving use of predicted chemical data in experiments listed above; total number of groups - CH @ 2 CH/month
   CH per year = 48
(8) Meso-α scale predictability studies to determine the impact of resolution, initial data, initialization schemes, and model physics on predictability in 0-48 h range: total number of groups - 3 @ 20 CH/month CH per year = 720.

Total CRAY-1A hours per year = 3,948 (approximately 65 percent of a CRAY or 12 percent of an AVC).

Other Computational Characteristics Required

The speed of a Class VII computing system is its principal advantage for mesoscale research. The long runs required on a CRAY-1A in such areas as items 1, 3, 6, and 8 in the list just given would require elaborate "save" subprograms to guard against interruption, thus degrading machine output and requiring sizable expenditures of human reprogramming resources.

However, the Class VII system must have other characteristics in order to serve mesoscale research adequately. Among them are the following:

(1) A user-accessible central core storage of at least two million 64-bit words. Although a user can make do with lesser storage, considerable research time is lost when the user must devise routines to input and output model data to and from peripheral devices. In addition, it makes the user more dependent on that particular computer system.

(2) Reliable storage of model-generated data, as well as an efficient microfilm or microfiche plotting capability.

(3) Diagnostics clearly written and easily interpreted, with an adequate number of consultants available to answer questions concerning problems with programs.

Impact of Observational Capabilities on Computer Resources

The development of new observational capabilities on the meso-γ scale, in satellites, radars, aircraft, and automated ground networks, can have both direct and indirect impacts on computer resources. The direct impacts stem from the analysis and display of data generated by these observational systems. For example, individual Doppler radars can be readily processed on mini-computers, whereas the synthesis, display, and analysis of a group of three to five radar systems will require the use of CRAY-1A level resources.

The availability of new high-resolution satellite imagery will provide valuable data for initializing models of both terrain and synoptically induced mesoscale systems. Spatial gradients of surface temperature and moisture are known to play a critical role in the subsequent evolution of these systems. With both types of systems, outside of
detailed observational programs such as SESAME and PROFS, satellite imagery may provide the only effective tool with which to monitor mesoscale circulations in order to document their frequency and vigor for operations and research.

Another valuable new tool is the portable automated surface observing system which can provide detailed analyses of mesoscale wind fields. Already the tool has been shown effective in monitoring the convergence field of mesoscale systems in a number of large observing experiments carried out by NCAR, universities, and other research groups.

Such systems not only provide initial data and validation for models, but they also provide the opportunity to monitor and to experience the development and evolution of mesoscale systems in real time.

The biggest impact of new observing systems will be to provide new data which can initialize mesoscale models and challenge modelers to simulate the observed phenomena. Many of the uses of the new data sets have already been accounted for in the above estimates of computer time required by the models. A reasonable estimate for the additional requirements for data processing is an additional 10% of the estimate previously given, or 400 CRAY-1A hours.
CLIMATE RESEARCH

(Drafted by W. Lawrence Gates, Oregon State University, in consultation with Robert Dickinson and Warren Washington, NCAR.)

The study of climate has received as much national attention in the past several years as any area of atmospheric research. Interest in the possibility of reliable predictions for the next season has grown among policy makers in the United States and other countries. Great interest has also been expressed in studies to determine the impact of the atmospheric by-products of human activity (e.g., carbon dioxide (CO₂) and other trace gases and particles) on climate, especially in those areas of the world that are critical to world food supplies.

At the same time, the scientific community's emphasis on climate research has increased. More of scientists are recognizing that the art of numerical modeling has reached a state where we can be relatively optimistic that over a period of one or two decades, models will be useful in predicting climate a month to a season in advance, in determining the effects on climate of various human activities, and in furthering our understanding of longer-term climate trends.

While the status of both observation and theory is progressing well, the availability of computing resources is becoming an increasingly serious limitation on progress. This situation stems from the very nature of climate and the great number of factors that influence it on all time and space scales.

Climate research has enormous requirements for computation. The number of climate questions which can be satisfactorily answered only through experiments using comprehensive climate models are increasing rapidly. In addition, we are now sure that such experiments will have to be extended over a much larger number of cases and/or over a much longer time interval than previously thought. One of the expected consequences of the availability of expanded computing resources at NCAR will be a significant increase in the number of university scientists involved in climate simulation and sensitivity studies in order to attack these scientifically attractive and significant questions. When we add to developments the extensive diagnostic calculations required to interpret the results of climate model simulations and the need to assemble new global climate data sets from both conventional and satellite observations, climate research in the next five to ten years will clearly require prodigious new computer resources.

Five areas of climate research are expected to undergo rapid expansion in the next few years within the community of university and NCAR scientists. These research areas are closely related to environmental issues of increasing national and international concern. Significant opportunities for scientific advances will go untapped, however, if the necessary computer resources are not provided. Brief comments on each of these areas are presented below, with an emphasis on their use of
computer-intensive climate models. It appears that vigorous research programs in these areas will alone require the resources equivalent to about two CRAY-1A computers.

Research Problem Areas

1. Seasonal forecasting. The national welfare and economy would benefit significantly from improvements in forecasting the general character of the coming season's climate (e.g., wet/dry, cold/warm). Research to improve our ability to make such forecasts has been prescribed by the U.S. Congress in the National Climate Program Act of 1978. The skill of such predictions as currently made by combined statistical-empirical methods is quite low. The exploration of the potential of predictions with climate models has not yet begun in earnest, due at least in part to the lack of sufficient computing resources.

In contrast, one of the most exciting and promising developments in climate research in recent years has been the confirmation of global-scale teleconnections between conditions in the equatorial upper ocean and atmospheric circulations in middle latitudes. Relatively warm water in the central equatorial Pacific in the fall is related to the occurrence of an anomalously cold winter the following year in the eastern United States. This interaction has itself recently been identified as part of the so-called Southern Oscillation, in which a large fraction of the tropical ocean and atmosphere is involved.

An understanding of these events is currently the object of intensive theoretical and empirical research. Applying this understanding to operational seasonal forecasting in five to ten years' time will, however, require models, data acquisition systems, and a level of computing support not now available. The first step is an extensive program of numerical experimentation to discover the most critical processes and their necessary resolution, and to assist in the design of effective observing and/or monitoring systems.

Studies have been made over the last several years to clarify the dependence of monthly and seasonal climate anomalies on ocean temperature anomalies. As previously stated, the largest influence appears to come from the tropical oceans, and coupled ocean-atmosphere models that can forecast ocean surface temperatures will therefore be required if we are to attain useful seasonal forecasting. Models capable of predicting the results of other physical processes such as soil moisture and snow cover, on time scales of a month to a season, are also likely to be required.

Climate models will also be indispensable in determining the degree and nature of the potential predictability on seasonal time-scales through the assembly and analysis of ensemble forecasts. (That is, instead of making a single forecast with a model, a large number of forecasts are made with slight changes in boundary conditions, such as ocean temperature.) Seasonal forecast models will not only require many integrations but may also eventually require high resolution (e.g., 200 x 200 km in the horizontal and 15 vertical layers) to resolve the regional details. Given even the current number of individuals and groups
expected to be involved in such work, about one-fourth to one-half of a
CRAY-1A computer would be required from the mid-1980s onward to carry out
the needed studies.

2. Climatic effects of CO₂ and other trace gases. The possible
climatic effects of the steadily increasing levels of CO₂ in the atmo-
sphere (due principally to the combustion of fossil fuels) is currently
receiving a great deal of attention. In the past few years, about a
dozen varied, simplified models have been applied to this problem. Simu-
lations are currently under way with several different atmospheric
general circulation models (GCM) to explore the atmospheric effects of
doubled CO₂. There is an emerging consensus that the equilibrium
globally averaged annual warming will be approximately 2°C, with a
poleward amplification. There is less agreement as to the accompanying
changes of cloudiness, precipitation, and surface moisture in various
regions of the world. Much further simulation (i.e., longer runs) using
GCMs is required to establish the seasonal and geographical patterns of
the CO₂-induced changes of temperature and precipitation at levels of
statistical significance useful for estimating the agricultural and
economic impacts.

Comparable attention needs to be given to the climatic effects of
rising levels of atmospheric trace gases, especially chlorofluoromethanes
and tropospheric ozone. The collective warming effect of all such gases
is perhaps 50% of that due to CO₂. Sensitivity experiments are required
to establish whether or not the climate change due to these gases will
simply represent an amplification of that due to CO₂ or whether they will
introduce additional, qualitatively different patterns of climate
change. (Computer resources required for this work is additional to the
requirements given for related studies described in the section on atmo-
spheric chemistry.)

It is recognized that the ocean plays a major role in the CO₂-
climate problem by virtue of its high heat capacity (and therefore slow
thermal response), and through its direct role in the carbon cycle by
absorption and subsequent transformation of CO₂. To authoritatively
determine the climatic impacts of CO₂ (and possibly of other trace gases
as well), it will be necessary to apply models of the coupled ocean-
atmosphere system, and to use a scenario that assumes a gradual increase
in atmospheric CO₂ over several decades rather than the sudden doubling
or quadrupling now used. Integrations of coupled atmosphere-ocean GCMs
will therefore have to be carried out over periods of 30-50 years of
model time, and will require the commitment of very substantial computer
resources. Scientists now involved in this area of research could
usefully employ up to one-half of the resources of a CRAY-1A, and within
five years, the equivalent of an entire CRAY-1A dedicated to this area of
research will be needed. Major groups now involved include the NCAR
Climate Section, the University of California at Los Angeles, and Oregon
State University.

3. Paleoclimates. The reconstruction of past climates by numeri-
cal models provides a unique opportunity for calibration of the models
as well as important information on the possible behavior of the climate
system. Past research using NCAR computing facilities has either used
relatively simple models or atmospheric GCMs in the case of the ice-age
climate of 18,000 years ago and the Cretaceous climate of 100 million
years ago. It is known that the earth's climate has undergone several glaciations in Pleistocene times in apparent response to the variations in orbital parameters, and geological evidence is rapidly accumulating that the climate has undergone profound changes in response to the changing distribution of oceans and continents over geological time ranges.

The systematic simulation of palaeoclimates is an important goal for the university community and NCAR over the next five to ten years. At present this is nearly virgin territory, and its exploration is expected to provide valuable insight into the nature of climate systems in general. It will require coupled atmosphere-ocean-ice-sheet models, including appropriate information on the orbital parameters and such factors as the earth's rotation, the atmosphere's composition, and the configuration of land and ocean basins. For selected times of particular climatic interest (and for which there is a reasonable assembly of geological and environmental data for use as boundary conditions or verification), a productive approach would involve a sequence of atmospheric and upper-ocean simulations in order to establish the seasonal climate in equilibrium with a given ice-sheet topography, followed by an integration over perhaps a thousand years with an ice-sheet model as forced by the temporally fixed climate. Such a program will require an extensive commitment of computer resources over the next five to ten years. The general area of palaeoclimates is also of great theoretical interest to university scientists.

4. Regional climates. The problem of relating regional-scale climate (e.g., on scales of 1000 km) to that on the large scale is now recognized as a critical element of climate research, and is an area of great practical interest as well. It is, after all, on the local scale that the impacts of climate and climatic change are felt, and without the ability to translate climatic information from the large scale to the regional scale, the results of models with only large-scale resolution will be of limited practical use.

To go beyond the kinds of regional inferences that can be drawn statistically from information on the regional topography and the observed large-scale climate, it will be necessary to explore the embedding of a regional or mesoscale model within a conventional GCM. With the increasing emphasis now being given to modeling mesoscale atmospheric phenomena, its application to climate will soon become a new and important research frontier. While emphasis at first may be given to U.S. climate, this approach would also be useful for studying monsoon systems and the effects of land-use changes on tropical forest areas. Computer resources must be provided to examine such questions as one-way versus two-way mesoscale coupling to the large scale, as well as for an extended experimental program with a variety of model formulations.

This approach may also be used to provide regional detail in the climate change due to increasing CO₂ or in seasonal climate forecasts. However, if mesoscale models are to achieve computational stability, quite short time steps (e.g., of a few minutes or less), are
required, and the computing demands are severe. It is expected that preliminary development work will, by the mid-1980s, require about one-fourth of the resources of a CRAY-IA.

5. Improved model parameterizations. To support the areas of climate model application described above, renewed attention must be devoted during the next decade to the improvement of the models' parameterizations of those physical processes which are likely to be critical to sensitivity studies and to climate prediction. Among such key processes are land surface effects, the behavior of ice and snow, cloud-radiation feedbacks, and orographic effects. The exploration of each of these effects will require significant computer resources in the coming years for the necessary sensitivity and resolution studies.

Land-surface processes needing attention include the interactive modeling of biomass growth, modeling the effects of vegetation on friction and on the surface budgets of heat and moisture, and the effective parameterization of the varied small-scale patterns of surface effects onto the large scale. Such parameterizations will be of immediate use in simulations of the climatic effects of deforestation and in model studies of the dynamics of desertification.

Ice and snow effects needing further research include the behavior of surface snow (whether on bare land, sea ice, or land ice), and the progressive changes in its optical, thermodynamic, and hydrologic properties. These parameterizations will be of particular importance in model studies of the behavior of ice sheets grounded on submerged bedrock, as is the case in the West Antarctic.

Cloud-radiation feedback processes needing attention include the development and testing of improved algorithms for cloud formation; for the effective absorbing, reflecting, and scattering properties of clouds in terms of their liquid water content and drop-size distribution; and for the effects of parameters such as cloud height and thickness on the ambient temperature, moisture, and vertical motion. Such parameterization is of particular importance in the improvement of the simulation of the net radiative effects of large-scale cloudiness and hence in the maintenance of the planetary heat balance. High-level cirrus and low-level stratus are believed to be especially important. This research will require extensive model sensitivity tests in order to make effective use of the satellite radiance data to be collected over the next five to ten years. In conjunction with these studies, more attention will need to be devoted to the details of other hydrologic processes, especially precipitation.

Orographic effects in climate models are in particular need of improved representation, since orography has a profound influence on the quasi-stationary and transient behavior of the atmosphere on both the mesoscale and the planetary or large scale. The treatment of flow near mountains in most GCMs does not ensure the approximate conservation of potential enstrophy, for example, and uses smoothed terrain data which probably systematically underestimate the mountains' effects. Global models currently use orography only on a $10^2$-$10^3$-km scale, although data sets for orography down to a 10-km scale are now available. Extensive numerical experimentation with improved orographic treatments in GCMs is likely required for the models' successful application in both seasonal forecasting and climate simulations. It is expected that within five
years the ongoing programs to further improve model physical parameterizations will need about one-fourth of the equivalent of a CRAY-1A for the requisite sensitivity studies.

**Summary of Computing Requirements for Climate Research**

The total computer resources (in units equivalent to the capability of the CRAY-1A) in the five research areas just discussed are as follows:

<table>
<thead>
<tr>
<th>Area of Research</th>
<th>Range of Requirements (CRAY-1A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal forecasting</td>
<td>0.25 to 0.50</td>
</tr>
<tr>
<td>Climate effects of CO₂ and other trace gases</td>
<td>0.50 to 1.00</td>
</tr>
<tr>
<td>Paleoclimates</td>
<td>0.25</td>
</tr>
<tr>
<td>Regional climates</td>
<td>0.25</td>
</tr>
<tr>
<td>Model parameterizations</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.50 to 2.25</strong></td>
</tr>
</tbody>
</table>

In addition to university use, this table includes the estimated use by the NCAR Climate Section for development and use of NCAR community climate models (CCM) and for research carried out directly by NCAR scientists, in most cases jointly with colleagues elsewhere.

In the years 1984 onward, 10 to 20 groups across the nation are expected to use the NCAR CCM. In addition, experiments using greatly increased computer resources, compared to present usage, will include studies of CO₂ and trace gases using coupled ocean-atmospheric models (see subsection 2 above), high-resolution climate models with improved simulations of the formation of clouds and their subsequent radiative feedbacks, as well as improved parameterizations of the effects of vegetation and other processes near the earth's surface (see subsections 1, 4, and 5 above). The latter work will require models with greater horizontal resolution and more layers in the vertical than those now available, with a corresponding increase in computational power. These requirements are included in the table above.
ATMOSPHERIC CHEMISTRY AND AERONOMY

(Drafted by Julius Chang, Lawrence Livermore National Laboratory, University of California, in consultation with Michael McElroy, Harvard, Shaw Liu, National Oceanic and Atmospheric Administration, and Ralph Cicerone and Robert Dickinson, NCAR.)

Public concern about environmental and economic issues has been one of the driving forces behind the rapid increase in research on atmospheric chemistry. In the past decade, a large number of scientists have been involved in attacking the basic and applied questions related to the impact of the by-products of human activity on the chemistry of the atmosphere, particularly the stability of the stratospheric ozone layer and the formation of acid rain.

While considerable progress has been made in investigating such phenomena as acid rain and chemical events in the stratosphere, quantification of these processes to provide truly reliable information for policy makers still lies in the future. The foundation of basic knowledge of atmospheric chemistry also needs much strengthening.

Comprehensive three-dimensional models that couple chemical species and meteorological processes are becoming an increasingly important research tool in basic and applied studies by the university-NCAR community. These modeling activities are expected to require large increases in computer resources in the near future. Similarly, the analysis of large data sets generated by satellite remote-sensing techniques will make sizable demands on computing resources. In this section, we discuss six research areas that are expected to make especially fruitful use of future computer resources at NCAR and elsewhere. These areas are of great interest to the scientific community, of considerable practical importance in dealing with national concerns, and intrinsically so complex that less computer-intensive approaches are not likely to achieve the basic goals of these problem areas. A computer resource at least equivalent to that of an entire CRAY-1A computer at NCAR will be required, if computing resources are not to become a major limitation on research programs in these areas in the next few years.

In considering future computing requirements, it is essential to consider thoroughly the strategies required to achieve basic objectives with the most efficient use of resources. Excessive duplication of modeling development and research studies would greatly increase demands on both computing resources and scientists to a point where sizable inefficiencies would result. Sharing of model development activities and research tasks must be actively promoted. In particular, the community must develop more institutional arrangements such as those related to NCAR's Community Climate Model to serve as focal points for future large-scale modeling activities in atmospheric chemistry and aeronomy. The estimates of computer requirements in this section assume that such institutional arrangements will be conceived and put into effect to the extent required to achieve efficient use of resources.
Modeling the Chemistry of the Nonurban and Global Troposphere

The chemistry of the global-scale troposphere will receive increasing attention over the next decade. We have the ability now to measure concentrations of trace gases with concentrations as low as a few parts per trillion by volume. Systematic observations are available for carbon dioxide (CO2) at a number of sites since 1958 and for fluorocarbons (specifically CF2Cl2, CFC13), methyl chloroform (CH3CCl3), and nitrous oxide (N2O) over the past three years. We anticipate that the data base will expand in the years to come and that other gases, such as methane, carbon monoxide (CO), and oxides of nitrogen, will be added to the list of species measured. Instrumentation has been developed also for special measurements of important radicals such as nitric oxide (NO), hydroxyl molecules (OH), and other compounds such as straight-chain and ringed hydrocarbons.

A major current target of tropospheric chemistry is to develop an understanding of the complex interaction of the atmosphere with the biosphere, a necessary prerequisite to comprehensive assessment of the effects of human activity on the atmosphere. Among questions now being addressed are: to what extent is the rise in well-documented worldwide atmospheric CO2 due to burning of fossil fuel, and how are CO2 concentrations modulated by changing land-use practices and slash-burn agriculture? What are the processes that control oxides of nitrogen (NOx) in the natural tropospheric environment, and how are they disturbed by urban and agricultural emissions? What factors regulate tropospheric ozone (O3) in the absence of human activity? How is ozone disturbed by industrial sources of NOx and hydrocarbons or by aircraft? What are the essential features of the natural sulfur cycle in the troposphere? What processes control the production and distribution of aerosols and the chemistry of precipitation, particularly acid precipitation? Many of the answers to these questions have an obvious connection to aspects of climate research described elsewhere in this report.

Answers to these questions will require development and use of imaginative and challenging models, with experimental and observational strategies linked to theory to an extent unprecedented and indeed unnecessary in the past. An important first step is the integration of realistic chemistry into global circulation and climate models. Among the complicating factors are the following: (a) Important chemical elements of the troposphere are not in local chemical equilibrium, (b) transport plays an important role in distributing chemical species whose lifetimes range from days (sulfur dioxide) to weeks (NOx) to months (CO); (c) the wide range of lifetimes poses difficulties for the description of their distribution, requiring a complex transport model; and (d) lifetimes for N2O and the halocarbons extend to values in excess of a hundred years, with removal of these gases mainly in the stratosphere. Thus in studying global tropospheric chemistry, a time-dependent
atmospheric circulation model is needed. Such a model would have a horizontal resolution of approximately 200 km, with approximately 15 vertical grid points or comparable resolution in other representations. The horizontal resolution is dictated by the need to include essential elements of tropospheric dynamics and to describe the more important heterogeneity of surface sources and sinks. The vertical resolution is required to provide adequate troposphere-stratosphere exchanges, in order to account for removal of particular species in the stratosphere (CF₂Cl₂, CFC₁₃, methyl chloride, and CH₃CCL₃, for example) and to account for downward transport of radicals such as NO and for O₃. Model runs of approximately 20 years' model time will be necessary. Other chemical models with simplified meteorological coupling will also be required. For efficient pursuit of the current goals of tropospheric chemistry, 20 to 30 percent of the resources of a CRAY-1A will be required.

**Stratospheric Global Models**

Since the early 1970s, steady progress has been made in understanding the photochemistry of the stratospheric ozone layer. Species such as fluorocarbons and methyl chloroform from industrial processes and consumer products, NOₓ from high-flying aircraft, CO₂ from fossil fuel combustion, and N₂O from fertilizer all pose threats to the ozone layer and hence to the global environment. This effort therefore has provided, in both scientific and public-interest terms, the principal motivation for a sharp increase in stratospheric chemistry research in general. That is, to understand all the impacts on the stratospheric ozone layer, we must determine the sources, sinks, and distributions of many trace species in the stratosphere, as well as the sensitivity of one species as perturbations in others occur.

A principal factor in research progress on stratospheric chemistry has been the development of theoretical models for theoretical analysis, for prediction of the fate of trace constituents, and for the planning and interpretation of field experiments. Such models are indispensable to integrate and understand the complex interactions among all the processes involved.

For the past decade, one-dimensional stratospheric photochemical models have played a central role in developing our knowledge of the stratospheric ozone layer. These models include a parameterized vertical transport prescription, detailed descriptions of the photochemistry, and sometimes a reasonably detailed radiation-temperature sub-model. The computation time per experimental run ranges from a half-minute to several minutes of equivalent CRAY-1A central-processing-unit time, depending on the complexity and structure of the individual model. However, the next important steps in reducing uncertainties in model predictions of anthropogenic perturbations of atmospheric ozone layer require three-dimensional models. For example, a central issue is the
extent and consequences of dynamical-chemical interactions in the lower stratosphere. While two-dimensional models have provided initial insights on the multi-dimensional aspect of ozone layer chemistry and dynamics, only three-dimensional models can provide adequate, self-consistent analysis of the interactions involved. These models are necessary to investigate the quantification of solar-induced or dynamically driven natural variations in ozone distribution; the sources, sinks, and distribution of water vapor; the global distributions of other trace species, including ozone; the transport of man-made pollutants and their impact on the atmosphere; stratospheric and tropospheric exchange processes for both inert and reactive trace species; and potential climatic impacts of chemical perturbations.

A dozen or so two-dimensional stratospheric chemical models exist in the United States, distributed among universities, government laboratories, industry, and NCAR. A typical two-dimensional model, such as now used at NCAR, with mean Lagrangian transport, turbulent mixing, and full chemistry, has about 25 latitudinal zones, 50 vertical layers, and more than 30 trace species and 120 reactions. It takes about one hour of CRAY-1A CPU time per model year. For many problems such as the impact of man-made pollutants, it would take ten or more model years to reach the state of interest. Consequently, even with the present set of two-dimensional models (in the absence of further refinements) several hundred hours of CRAY-1A time per model per year would be needed to fully utilize these two-dimensional models.

Three-dimensional models of stratospheric chemistry are now under development. They will incorporate all important and relevant aspects of existing scientific knowledge and are limited only by computer capacity and capability. They can therefore provide a self-consistent assessment of the nonlinear interactions among, and consequences of potential perturbations to, the various stratospheric chemical-dynamical systems. By the end of this decade, a functional model is expected to be available. Based on an analysis of the resolution requirements for adequate representation of various physical processes, a model with a five-degree horizontal grid and 20 layers in the vertical is needed. Such a model would require several hundreds of hours of equivalent CRAY-1A running time per study.

Obviously, such a three-dimensional model is beyond the currently available computing capability. Even a cautious model development program, along with the ongoing one- and two-dimensional model experiments, would require computational resources equivalent to one-half of a CRAY-1A, at the minimum.
Regional Air-Quality Modeling

Public and scientific concern about regional air quality and long-range transport of air pollutants started in the 1950s in Europe, when chemical analysis of rain and snow showed possible transport of air pollutants, such as sulfate, from western Europe into Scandinavia. The same concerns have been evident in the United States for the past 15 years. Major targets of concern in the study of regional air quality are ozone, wet and dry acid deposition (sulfate and sulfuric acid, nitrate and nitric acid), NOX, other trace elements, and visibility issues related to health, transport of substances, etc.

Many of the environmental effects of the pollutants are well-documented. However, understanding the factors that control the transport, deposition, and chemical transformation of the pollutants must be well understood if effective control strategies are to be designed. At present they are too poorly understood. For example, while elevated oxidant levels (O3 and some NOX) are often found over multi-state regions, and while long-range transport of anthropogenically emitted hydrocarbons and NOX is suspected to be the precursor of these elevated oxidant levels, we are ignorant about the processes that limit the rates at which these oxidants are produced and discharged, or, in some cases, where in the atmosphere the processes occur.

Key questions of regional air quality are primarily the following: What are the sources and sinks of ozone? How is nonurban ozone affected by anthropogenic activities? What are the major processes that oxidize sulfur and nitrogen compounds to sulfate and nitrate? How far is the acidic material transported? Given the answer to these questions, what then is the source-receptor relationship in the emission and deposition of acidic material? What is the impact on atmospheric aerosol concentrations, visibility, and radiation due to anthropogenic activities? The spatial scope of research for these questions ranges from the urban scale to major portions of a continent.

Clearly, modeling of these various transport and chemical processes, in conjunction with laboratory and field measurements, is needed for an integrated attack on these problems. Realistic representations of the transport and physical processes of the cloud and precipitation are a major task. In addition, detailed mesoscale meteorological models are required to provide the framework for realistic simulations of regional air chemistry processes. The horizontal resolution required is 20 to 50 km, with 15-20 vertical layers. The homogeneous and heterogeneous chemical processes coupled with these models will include the reactions of O3, water vapor, hydrogen radicals, ammonia, NOX, oxides of sulphur, hydrocarbons and their derivatives, aerosols, water droplets, and ice particles.
We anticipate that within the next two years, at least two regional air-quality models will be developed to carry out research studies of the problems just discussed, using the NCAR computers. These activities are expected to require 15-25% of the resources of a CRAY-1A computer, excluding that necessary for developing and testing the required mesoscale models, which are discussed elsewhere in this chapter.

**Thermosphere-Ionosphere Modeling**

Our understanding of the physical processes above 100 km has advanced to a point where comprehensive three-dimensional numerical models are becoming an essential research tool in order to reflect realistically their intrinsically three-dimensional nature. The diurnal and latitudinal variation of solar heating, together with the joule heating and momentum added by auroral-magnetospheric convection processes, drive large-scale regular and irregular wind systems. Extreme ultraviolet solar radiation and high-energy auroral particle precipitation also drive important chemical processes, including those that produce the ions and electrons responsible for the ionosphere and cause the dissociation of molecular species into atomic species. Ion drag provides the major sink for atmospheric momentum in the ionosphere and thermosphere, and winds in turn transport ions in important and interesting patterns. The distributions of the major gases—atomic oxygen, nitrogen, and molecular oxygen influence the pressure patterns that drive the winds and in turn are redistributed by the winds. Atmospheric tidal disturbances and gravity waves enter the thermosphere from lower regions of the atmosphere and act as sources of momentum and small-scale eddy mixing. The small-scale eddy mixing, together with vertical molecular diffusion, in large part determines the vertical variations of the mixing ratios of the various species. Ions drift due to electric fields generated by wind in interactions with the magnetic field.

Over the last five to ten years computer models of many of these individual processes have been developed, and a considerable fraction of the recent progress has been made by university and NCAR scientists using the NCAR CRAY-1A computer. Now in progress at NCAR is the development of a thermospheric general circulation model that will synthesize all the processes described above. This model uses as a framework a five-degree horizontal resolution dynamic model derived from the fourth-order accuracy grid-point tropospheric general circulation model previously developed at NCAR. The model now satisfactorily generates winds due to solar and auroral forcing. Current work is directed to inclusion of compositional variations, coupling to lower atmospheric tides, and coupling to ionospheric formation and dynamics.

Progress on further development of this model is now restricted by limitations of computing capacity and memory. These limitations are expected to become much more severe in the next several years as a result of two trends:
(1) The considerable increase in the number of model variables, with further coupling of composition and ionospheric and electrodynamic processes. This trend implies large increases in the required computer time and memory use.

(2) An increasing number of university scientists who are using the NCAR thermospheric general circulation model for their own or collaborative studies, with consequent further demands on the computer resources.

By mid-decade, these activities are likely to require in excess of 20 percent of a CRAY-1A or equivalent.

**Planetary Atmosphere Models**

Much of our current knowledge about the atmospheres of other planets has been developed over the last ten years as a consequence of the National Aeronautics and Space Administration's planetary exploration program. Some studies of planetary atmospheres, especially Venus and Mars, have successfully used the NCAR CRAY-1 in the last few years. Even if further observational exploration is curtailed, theoretical modeling at a continuing or accelerated pace is required to exploit the extensive set of data already gathered. No particular modeling program will be an extremely large program. Rather, one to two dozen modest modeling efforts, the sum of which could place a considerable demand on NCAR computing resources, will develop.

This area will continue to be attractive to many university scientists and will remain an especially fertile training ground for graduate students. The atmospheres of Mars and Venus will continue to be of special interest, but those of the their larger planets and larger moons will also be modeled in much more detail than they have been.

In addition, a considerable increase in demand on NCAR resources will result from (a) a larger number of intermediate-scope modeling activities, and (b) an increase in large three-dimensional modeling projects that convert models being used for terrestrial studies. Examples are the three-dimensional model of the Venus thermosphere being developed jointly by University of Michigan and NCAR scientists and a detailed Martian global climate model derived from the NCAR Community Climate Model.

The total of planetary atmosphere modeling activities at NCAR is expected to require five to ten percent of a CRAY-1A or equivalent over the next five years.
Satellite Data Processing and Analysis

During the past few years, techniques have been developed to observe the atmosphere from satellites in ways that have greatly improved our knowledge of the global distribution of various important chemical constituents in the stratosphere. Through the use of satellite-borne instruments, scientists have made the first observations of the global distribution of O₃, H₂O, nitric acid, nitrogen dioxide, and other trace constituents. Using global maps of temperature derived from satellite observations, they have also, for the first time, been able to calculate winds and the transport of heat and momentum in the upper atmosphere.

The NCAR CRAY-I and associated computing systems at NCAR have been especially useful in this work, particularly in objective analysis and mapping using memory and graphics capabilities, detailed calculations for designing these experiments, and analysis of very large data sets.

During the next decade, satellite experiments are expected to achieve more refined vertical profiles and global maps of trace constituents important to the stratospheric heat balance and hence climate, as well as to the fate of the ozone layer. Other experiments will measure the response of the upper atmosphere to variations in solar output, provide direct and indirect measurements of global stratospheric winds, and study the origins of plasmas in the thermosphere and outer ionosphere.

It is anticipated that at least four groups will be active in this work. While it is expected that much of the initial data processing and some of the analysis will be done at NASA centers, demands on NCAR computing resources are expected to be substantial. This will be particularly true when scientists other than the relatively small original group of experimenters begin to explore the information contents of these data. In addition, the satellite data will spur sophisticated data interpretation involving the theoretical models previously described.

By the end of the 1980s, it is anticipated that this type of work will require resources equal to ten percent of a CRAY-I.

Summary of Computer Requirements

The requirements for computing power discussed in this section are given below in CRAY-I units:
<table>
<thead>
<tr>
<th>Subject</th>
<th>CRAY-1A Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropospheric Modeling</td>
<td>.20 to .30</td>
</tr>
<tr>
<td>Stratospheric Global Models</td>
<td>.50</td>
</tr>
<tr>
<td>Regional Air Quality Modeling</td>
<td>.15 to .25</td>
</tr>
<tr>
<td>Thermospheric-Ionespheric Modeling</td>
<td>.20</td>
</tr>
<tr>
<td>Planetary-Atmospheric Models</td>
<td>.05 to .10</td>
</tr>
<tr>
<td>Satellite Data Processing and Analysis</td>
<td>.10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.20 to 1.45</strong></td>
</tr>
</tbody>
</table>
OCEANOGRAPHY

(Drafted by Peter Rhines, Woods Hole Oceanographic Institution, in consultation with William Holland, NCAR.)

Over the past decade, the research linkage between atmospheric science and oceanography has become far stronger than it had been previously. There are four principal reasons for this development. First, the two areas of science share an essential interest in geophysical fluid dynamics, and much of what is learned about such processes in the ocean are applicable to the atmosphere and vice versa. Second, to understand adequately the nature of climate and climatic change, it will be necessary to couple a fully dynamic model atmosphere with a fully dynamic model ocean. Third, even to delineate the overall behavior of the oceans over periods of years to decades (e.g., changing major ocean currents and temperature distributions), coupled models also will be required. Fourth, the major computing resource available to ocean modelers has been at NCAR, an institution with a small but active oceanography program embedded in a larger program of atmospheric research.

The current and prospective computing needs of the oceanographic community, particularly of scientists who develop and use ocean models of various types, has recently been documented in the National Research Council publication, An Assessment of Computational Resources Required for Ocean Circulation Modelling (National Academy of Sciences Press, 1982). Having surveyed 180 ocean modelers at 32 institutions, the authors of the report concluded that "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," and that "the projected 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."

These needs are expected to increase during the years after 1984, when there will be a rapid influx of new Ph.D.s who are attracted to physical oceanography and related studies by their scientific challenge and their importance to human affairs and the long-term health of the planet. The needs of oceanographic modelers should be met not only because their work is central to the exploration of an important intellectual frontier, but also because their work is related to such topics as climate and climate change, the transport of chemical wastes deposited in the oceans, navigation, fisheries, management of coastal waters, and prediction of storm surges that affect shipping and threaten coastal lands.

Progress in the Past Decade Using Sizable Computing Resources

The ocean research areas discussed in this section have shown particular vitality during the past few years, and progress in them has depended greatly on the use of numerical modeling techniques. The availability of advanced computers, particularly the NCAR CRAY-I, has been vital to the quantity and quality of the work accomplished.
1. Equatorial dynamics, monsoonal adjustments, equatorial jets, boundary currents. While analytical approaches using linear wave theory have been successful in studying these subjects, the numerical synthesis of these approaches with realistic forcing and geometry, and extension to nonlinear models, have been equally important and useful.

2. Regional models, including studies of tides, waves, and circulation in open domains (e.g., the Mid-Atlantic Bight, Bay of Fundy, Juan de Fuca Straits, North Sea). The goals of research in shallow areas, embayments, and continental shelf regions are mostly sea-level prediction (including storm tides), an understanding of the dispersal of pollutants, and general ecology studies. Dynamical effects of the marginal seas may have a strong influence on long-term climate change.

3. Beta-plane channel studies of waves and turbulence. These are truly interdisciplinary geophysical fluid dynamical studies that are applicable to problems ranging from atmospheric blocking to circumpolar ocean dynamics. They represent the simplest setting in which one can study the interaction between eddies and mean flow.

4. Geostrophic turbulence "process" models. A process model is one in which a few geophysical processes are studied in isolation (e.g., a 64 x 64 periodic square of fluid with the Earth's rotation, bottom topography, and finite amplitude eddy motions included, but without density stratification or lateral boundaries). This approach has helped lay the groundwork for more complex circulation models. Even with the advent of computers capable of handling general circulation oceanic models, process models will continue to be needed. Moreover, the computational demands of these models are greater than is generally believed, and computations that allow finer resolution will be needed in the future.

5. General circulation models. There are two classes of such models, ocean general circulation models (OGCM), which include much of the detail of the ocean (e.g., realistic coastline, topography, observed winds, and surface temperature) but no mesoscale eddies, and eddy-resolving general circulation models (EGCMs). EGCMs are capable of including mesoscale eddies in the oceans (which contain a strong component of the ocean's energy budget), but do not include all the important effects handled by OGCMs. Only in the past few years have these two approaches begun to converge; much work lies ahead, and the amount of progress will depend on the amount of computing resource available.

Recent work on both OGCMs and EGCMs has led us to a turning point in the study of ocean dynamics. Models are now sufficiently realistic to have true relevance in the interpretation of data. Moreover, we have recently reached interpretations of the basic fluid dynamical aspects of ocean circulations from which one may be able to distill a relatively simple set of guiding principles; only a few years ago, there was considerable doubt that this was practical or that consistent patterns of dynamical interactions could be inferred and used.
Ocean modeling has thus clearly come of age as an integrative tool. "Handshakes" exist between models and observations as well as between numerical models and analytical theory. The effort that requires the greatest computing resources tends to be the OGCM, particularly as OGCM studies involve the use of real data and interactions with other modeling and analytical studies.

Trends for the Remainder of the Decade

Future computer needs in oceanographic research can be discussed in terms of three particular kinds of studies that will require major enhancements in computer resources in the next several years. These studies involve ocean general circulation models, climate models, and satellite-derived data analysis with application to ocean problems.

1. General circulation models. Let us use a particular example to show why computing resources now need to be upgraded. The present predictive OGCMs take two forms, typified by Bryan's 20-level 77 x 77 model and Holland's three-layer 200 x 200 model. Bryan's is an OGCM with such boundary conditions and parameters as discussed before, but without resolution of mesoscale eddies. Realizing the limitations of the physics of the model when using observed winds and sea-surface temperature as boundary conditions, Bryan has also developed a partially diagnostic model which is forced internally by the difference between the model fields and the observed data. The mean circulation and density fields predicted reproduce, in a qualitative way, the known strong current systems; but the accuracy of the prediction of the thermocline, of the subtle but important meridional circulation, and of the flow near the western sides of the oceans (known to be related to eddies) is sensitive to the subgrid diffusion used in the model. Despite these limitations, Bryan's OGCM is a useful step toward full, thermally and mechanically active representation of ocean processes. Particularly at climatic time scales (decades and longer), the thermodynamic role of the ocean gains in importance. Thus the OGCM must be actively pursued, with increased attention to ice cover, high-latitude outcrop regions, and well-mixed surface layers.

Holland's EGCM approach has been to expand horizontal resolution but at the expense of vertical resolution and accuracy of prediction of the thermocline. A succession of models began to reach their full potential when an eddy-resolving three-layer model the size of the North Atlantic was developed. This GCM has the energetically dominant 100-km eddies well represented, yet with enough resolution to exhibit distinct geographical provinces. As a result of studies with it, the old idea that all the eddies in the ocean come from the western boundary current has been discarded. A vast region far from the Gulf Stream spawned eddies by baroclinic instability; and in these distant midocean regions one finally saw the realization of "process" models in quasi-homogeneous regions of vast extent. The study of the generation, equilibration, and propagation of eddies in this model alone has justified the extensive computer simulations required.
In the next few years, we can expect to reach a point where these two modeling approaches can be brought together and be fully coupled to the atmosphere. At present, oceanic layer-models on a beta-plane do not allow the density field to interact with the atmosphere. But as the horizontal extent of these models has increased, the need to include this interaction (where a given constant density layer intersects the sea surface) becomes more acute. As various investigators work on improved models that allow both ageostrophic effects and density prediction, they must deal with the question of the appropriate boundary conditions to apply at the sea surface. For certain phenomena, typically short-lived and weakly forced, the ocean may act as an independent system with little feedback. But on a longer time scales (years to centuries), the buoyancy flux feeds back into the atmosphere, and the ocean is no longer an autonomous system.

GCMs have now reached the stage where a rudimentary atmosphere will have to be attached. Geophysical fluid dynamical studies of importance remain even without this added complexity (e.g., using an insulating lid but allowing density outcrops to occur due to a strong mechanical forcing). For both reasons, a threshold has now been reached in ocean general circulation studies where new, and more costly computations are required and are merited. A true eddy-resolving basin scale model with active and realistic thermodynamics is possible, but only when enhanced computer resources are available to the university community. Such a model for the North Atlantic Basin would need on the order of 20 x 500 x 500 grid points and must be coupled to an atmospheric model. It should run for several model years to generate the needed data. It is estimated that computer resources ten times those currently available are needed to develop and apply this model.

2. Climate models. The discussion above concerns work that is separate from CILmate modeling, even though climate models may well involve a model ocean. At NCAR and the NOAA Geophysical Fluid Dynamics Laboratory, experiments with coupled ocean-atmosphere GCMs have been applied to the carbon dioxide warming problem. In addition, OGCMs are now beginning to be run for climatic time scales, while simplified climate models (like that of Held and Suarez) are also under development. These approaches need extensive further development before they can truly interact. To reach such interactions, the process-model and EGCM approaches must receive enough additional computing resource to allow them to have some of the attributes of the OGCMs.

Much progress can be made toward fully coupled, fully dynamic ocean-climate models if the capabilities of a class VII machine are available. Toward the end of this decade, however, another increment of computing power is likely to be needed to be able to complete the coupling of realistic oceanic and atmospheric climate models.

3. Satellite-derived data. Data from satellite-borne instruments, including wind stress, sea surface temperature, and perhaps sea level, will be an essential component of the oceanic observing system during the next decade. Satellite measurements derive their great value from their global coverage and ability to be averaged over time. The data volumes are very large, and sophisticated procedures are essential for extracting the quantities really needed. Thus, large amounts of data processing are an inevitable feature of the system. For example, archived data from a
single day's global coverage by the advanced very-high-resolution radiometer (one of the basic instruments used to infer sea surface temperature) fill 25 magnetic tapes. Though the initial processing of raw data streams is clearly the responsibility of the satellite operator, the conversion of the resulting archive into good science will involve the university and NCAR oceanographic community in individual research projects. In these projects, the effective flowering of initiative and creativity will depend on the existence of a substructure of powerful yet widely accessible data processing and analysis capabilities and shared experience.

Computer Resource Needs

The justification for additional computer resources at NCAR for the use of physical oceanography is documented in the National Research Council report, An Assessment of Computational Resources for Ocean Circulation Modelling. In that report, the significant progress achieved over the last decade in a number of subareas of physical oceanography is shown to be directly attributable to numerical modeling. Almost all of the large computations carried out by the academic community of physical oceanographers were done at NCAR.

The Academy report also details a number of important problems for which substantial additional computing resources are needed in the near future, in order to attack oceanographic problems with the same resolution of physical detail that was possible for atmospheric problems a decade ago. The Academy committee that wrote the report stated, on the basis of its own expertise in ocean modeling, that computational power equivalent to an entire Class VI (CRAY-1A-type) computer could be used effectively in such work by as early as 1984. The committee's estimates were substantiated by a careful survey of existing oceanographic groups engaged in numerical modeling. The committee therefore recommended that the equivalent power of a Class VI system be made immediately available to the academic ocean modeling community of the United States. The report also states that additional oceanographic computing demands, related to the processing of data from satellite observing systems, could easily double their estimated machine requirements.

Concluding Remarks

1. The interplay among models, theory, and observation. Numerical models of ocean circulations provide the link between analytical models and observations. Nearly every major problem in physical oceanography will require the development and use of models and large increases in computer resources as soon as they can be made available. In their simplest form, numerical models are extensions of the analytical approach; in their complex forms, they attempt to rationalize observations in terms of fundamental, often complex physical principles.

Our experience with the full discovery of mesoscale eddies and the resulting view of the role of theory in physical oceanography during the 1970s shows how observation, modeling, and theory interact. In the
early 1970s, there was considerable support for the idea that "classical" theory was no longer sufficient for studying ocean circulations, particularly when the strong dynamical role of mesoscale eddies began to be appreciated. It is now believed likely that the new effects of eddies can be folded into simple idealizations of the general circulation. Their effect, even when weak, is crucial in selecting among an infinity of possible steady circulations. In some fraction of the domain they can be so strong that the entire structure of the circulation depends on their average properties. Nonetheless, bounds can be set around the strong effects of eddies, showing how they totally control the small-scale mean flow in one area, drive moderate-scale abyssal flows in another, or sharpen a boundary jet in still another, yet leaving a vast range of planetary-scale weakly diffusive circulation branches essentially "steady." The classical theory that was to have been replaced has in fact remained valued and useful.

2. Chemical tracer studies. Observations of the ocean have changed so greatly in character over the past decade that they have driven theory and computer models into new realms; and even if no further extensive observations of the ocean were available, the currently available data are sufficient to advance the science rapidly in the next few years. "Lagrangian" fluid dynamics (in which fluid particles are followed), inverse theory, and shear-dispersion theory are all areas of current interest that have been stimulated by new kinds of data, particularly deep neutrally buoyant float tracks, chemical tracer observations, and satellite altimetry and radiometry. The effect of observations on the use of models and on computational requirements can be shown by a brief discussion of chemical tracer studies.

These studies have a long history. They typically involve tracing the growing number of dilute chemicals injected into the seas either by man or nature, particularly those with a recent history of injection. The patterns of transport and mixing (dilution) that are now being painstakingly measured provide a sensitive picture of the Lagrangian general circulation. Particularly, the slow meridional-vertical circulation and ventilation of the abyss are clear in these patterns. The sensitivity of the measurements (for example, one tritium atom in $10^{20}$ normal hydrogen atoms) is striking.

The challenge of such chemical tracer studies to computing resources is great. Rather than simply running a fluid dynamical model of the ocean and examining its force balances, one must inject tracers into a calculated flow and solve an advection-diffusion equation to predict their future. A computer model of the circulation may be accurate for the energetically dominant dynamics but inaccurate for the long-distance paths of fluid particles and long-time patterns of tracers. Distant boundary conditions have an embarrassing way of asserting themselves over tracer patterns, given time. The modeling challenge requires more concentrated effort than has yet been given to it.
3. Other problems requiring substantial new computer resources. In addition to OGCMs, climate models, satellite data analyses, and ocean tracer distributions, there are many other challenging problems in physical oceanography that will require both new observations and new computational resources in the next few years. Some of the problems that merit additional attention are high-latitude effects on climate (deep water formation ocean density outcrops), heat flux by ocean currents and eddies, the role of the cryosphere, the influence of bottom topography, the role of persistent structures (Gulf Stream rings and bullets), vertical transfers in the mixed layer (the mechanisms linking oceans and atmosphere), interannual variability in ocean gyres (the secular scale), and equatorial thermodynamic processes.

Need for Improved Data Links

The national pool of oceanographers involved in large modeling efforts is small but of high quality, and they are geographically dispersed. The utilization of an enhanced computing capability at NCAR will be most effective if improved data links are also provided to replace the currently existing low-speed telephone links. With enhanced power and communications, the NCAR computers can effectively meet the needs of those oceanographers whose work with various models is expected to advance the science significantly in coming years.

Overall Tables of Computing Requirements

There have been two recent studies of the needs of ocean modelers. Table 2 is taken from Ocean Models for Climate Research: A Workshop (National Academy Press, 1980). Estimates given in this table are only for ocean-climate modeling, and would be somewhat higher if all aspects of ocean modeling were discussed in this section. Table 3, from the more recent Academy study cited earlier, separates anticipated usage at the universities and NCAR from that expected at federal laboratories. The findings in both tables substantiate the case for computer resources equivalent to two-thirds to one CRAY-1A in the next several years for work anticipated in the universities and NCAR.
Table 3
COMPUTING ESTIMATES FOR OCEAN-CLIMATE MODELING IN THE EARLY TO MID 1980'S

A. Computing requirements for "typical jobs" in CRAY (or equivalent machine) hours

1. Moderate-resolution \((4500 \text{km})^2\) three-layer quasigeostrophic box model with \(\Delta s = 25 \text{ km}\) and \(\Delta t = 3 \text{ h}\):
   - 10 yr integration requires 10 CRAY h
   - 10 yr integration with irregular geometry requires 20 CRAY h

2. High-resolution \((1000 \text{ km})^2\) three-layer quasigeostrophic box model with \(\Delta s = 5 \text{ km}\) and \(\Delta t = 1/2 \text{ h}\):
   - 5 yr integration requires 33 CRAY h

3. Small equatorial primitive equation model (14 levels; 3000x2000, \(\Delta x = 1/2^\circ\), \(\Delta y = 1/4^\circ\), \(\Delta t = 1/2 \text{ h}\))
   - 5 yr integration requires 25 CRAY h

4. World ocean primitive equation model with \(\Delta s = 1^\circ\): 20 yr requires 100 CRAY h
   - Five levels \(\Delta s = 0.5^\circ\): 20 yr requires 1000 CRAY h

5. Small-high resolution channel with quasigeostrophic model = 20 yr integration requires
   - Primitive equation model = 75 CRAY h
   - 20 yr integration requires 1000 CRAY h

6. One-mode equatorial basin model: \((4500 \text{ km})^2\) with \(\Delta s = 60 \text{ km}\)
   - 10 yr integration requires 1/3 CRAY h

7. Two level ocean-atmospheric model \((\Delta y = 3^\circ + three zonal waves)\) with implicit time stepping
   - 10 yr integration requires 2/3 CRAY h

B. Estimated future needs

1. 20 investigators running 5 cases/yr of 10-h CRAY/case: 1000 CRAY h
2. 5 investigators running 5 cases/yr of 100-h CRAY/case: 2500 CRAY h
3. 2 investigators running 1 case/yr of 1000-h CRAY/case: 2000 CRAY h
   - TOTAL 5500 CRAY h

Table 4

PRESENT, PROJECTED AND DESIRABLE RESOURCE NEEDS FOR OCEAN CIRCULATION MODELING (UNITS: CPU HOURS/YEAR ON A CLASS SIX SYSTEM)

Usage at all Installations

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>Projected(a)</th>
<th>Desirable(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGCM/Climate</td>
<td>260</td>
<td>1167</td>
<td>2587</td>
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<tr>
<td>EGCM</td>
<td>309</td>
<td>643</td>
<td>1222</td>
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<tr>
<td>Regional/Process</td>
<td>615</td>
<td>1368</td>
<td>2462</td>
</tr>
<tr>
<td>Data/other</td>
<td>324</td>
<td>926</td>
<td>1332</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1508</td>
<td>4104</td>
<td>7603</td>
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</tbody>
</table>

Usage at Federal Laboratories

<table>
<thead>
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<th></th>
<th>Present</th>
<th>Projected(a)</th>
<th>Desirable(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGCM/Climate</td>
<td>157</td>
<td>659</td>
<td>814</td>
</tr>
<tr>
<td>EGCM</td>
<td>68</td>
<td>197</td>
<td>197</td>
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<tr>
<td>Regional/Process</td>
<td>266</td>
<td>763</td>
<td>1351</td>
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<tr>
<td>Data/other</td>
<td>250</td>
<td>773</td>
<td>1102</td>
</tr>
<tr>
<td>TOTAL</td>
<td>741</td>
<td>2392</td>
<td>3464</td>
</tr>
</tbody>
</table>

Usage at Universities and NCAR

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>Projected(a)</th>
<th>Desirable(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGCM/Climate</td>
<td>103</td>
<td>508</td>
<td>1773</td>
</tr>
<tr>
<td>EGCM</td>
<td>241</td>
<td>446</td>
<td>1025</td>
</tr>
<tr>
<td>Regional/Process</td>
<td>349</td>
<td>605</td>
<td>1111</td>
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<tr>
<td>Data/other</td>
<td>74</td>
<td>153</td>
<td>230</td>
</tr>
<tr>
<td>TOTAL</td>
<td>767</td>
<td>1712</td>
<td>4139</td>
</tr>
</tbody>
</table>

(From: An Assessment of Computational Resources Required for Ocean Circulation Modeling, National Academy Press, 1982.)

(a) "Projected" = Anticipated in 1984.
(b) "Desirable" = "Scientifically desirable and feasible" for each group surveyed.
SOLAR FLUID DYNAMICS

(Drafted by Peter Gilman, NCAR, in consultation with Dimitri Mihalas, Sacramento Peak Observatory, and Juri Toomre, University of Colorado.)

In the past decade, there has been a revolution in our concepts of solar phenomena. New satellite-borne and ground-based observations provide us with a picture of a complex and variable star with physically diverse regions that interact in many ways, and whose output varies on many time scales. Together with new data, such as those gathered from Skylab and the Solar Maximum Mission, new theoretical insights have led to a rapidly growing demand for various kinds of fluid dynamical calculations. We estimate that by the mid-1980s, this demand will require computer resources equivalent to a minimum of 0.50 of a CRAY 1-A machine, and that the need for a very large memory will make such calculations far more efficient on a Class VII machine.

The sun is a gigantic rotating ball of radiative fluid, permeated by magnetic fields. For physical understanding of the sun--dynamics of the solar interior, envelope, and atmosphere (including its extension into interplanetary space), we must model three-dimensional flows, allowing for magnetohydrodynamic, plasma, and radiative effects, as well as nonequilibrium processes in many regions. This effort has been at the frontier of our physical understanding, our modeling capabilities, and our computational resources.

A strong motivation for improved model calculations for the sun is the desire to understand the variability of its outputs--radiation, magnetic fields, and energetic particles--particularly those which reach the earth. Recently discovered correlations between various types of solar variability and anomalies in the earth's climate have spurred the search for physical explanations of how the two may be connected. An important component of this effort is the development of a full and coherent picture of how solar variability occurs.

Progress in understanding solar variability will have substantial benefits for astrophysics, particularly stellar physics. The sun is only one of many stars that have convection zones and manifest magnetic activity and cycles. A credible model for the "dynamo" that produces the solar cycle (a major type of solar variability) should, with appropriate parameter changes, also explain magnetic activity on other stars. Conversely, the variety of magnetic activity on other stars provides an important test of dynamo theory, and will doubtless improve solar dynamo modeling. Similarly, improved understanding of the interaction between radiation and fluid dynamics has numerous applications in astrophysics, in many cases to even more exotic behavior than the sun exhibits, such as pulsating stars and supernovae. The detailed observations provided by the sun allow extensive testing of radiation-hydrodynamic models, which can then be extended with much greater confidence to other, less well-observed, astrophysical objects.

The variable outputs of the sun originate in solar features of widely varying spatial scales, from below the smallest elements that can be resolved by ground-based observation (a few hundred kilometers) up to
the size of the sun itself (10^6-km diameter). The variations also occur on widely disparate time scales, from seconds up to the time scale of solar evolution. The greatest current interest in solar variability centers on time scales of a few days up to tens of thousands of years, partly because such events are of the greatest importance in studying the impact of solar variability on the earth's atmosphere, and partly because these are the time scales on which direct observations and proxy records of climate variability are now available.

The enormous ranges in both time and space scales of the critical phenomena of solar variability make mathematical modeling of their physics a formidable task, and the work must be divided into several parts. Among these are:

- Understanding the several distinct scales of thermal convection which occur in the sun and their interactions with magnetic fields to produce the ubiquitous, intense, but highly scattered, magnetic flux tubes seen at the solar surface;

- The aggregation of magnetic flux tubes into large coherent features such as sunspots, as well as the surrounding, even more complex, active regions;

- The generation and maintenance of the sun's global differential rotation by solar convection.

In addition, we must address the interaction among all these phenomena to produce the quasi-cyclic variation in solar magnetic fields, and in radiative and particle outputs, known as the solar cycle. That such interactions must exist is readily apparent from recent observations of solar luminosity, taken on the Solar Maximum Mission and Nimbus 7 satellites, that show luminosity drops of up to 0.2% associated with the passage of sunspot groups across the solar disk. Since sunspots are generated by the solar dynamo, we must understand how all these phenomena contribute to the solar cycle.

A parallel problem also requiring a concerted attack using large model calculations is the interaction of all the fluid dynamical processes with the solar radiation field. Not only does radiation ultimately provide the thermal driving for all the motions we see on the sun, but it also provides the diagnostics by which we observe the flow and detailed structure. In some ways, this problem is even more complex than time-dependent three-dimensional fluid dynamics and magnetohydrodynamics, because variations over the spectrum of radiation must be included. Also, the sun's atmosphere, from which the radiation we observe emanates, is an optically thin boundary layer within which radiation is transported freely. This transport leads to a global coupling among fluid elements, which greatly increases the computational complexity.

In the solar case, problems for which the interaction of radiation and fluid flow are of particular importance are: solar flares (very rapid events which release enormous amounts of radiative energy and, in some cases, high energy particles into the interplanetary medium), spicules
(intense jets of material feeding matter and energy into the upper solar atmosphere, which may play an important role in the energy balance of the solar atmosphere), and radiative damping of vertically propagating waves.

In the remainder of this section we will discuss each of the problem areas named above. We shall report the current status of work, and then discuss why, in each case, greatly increased resources are required for adequate scientific progress.

**Small-Scale Solar Convection**

Understanding what determines each particular convection scale and pattern is important because convection is, even just below the visible surface, the principal mechanism of transfer of heat from the interior, and so locally determines the sun's luminosity. And the same convection profoundly influences the observed magnetic structures.

The sun is observed to have several discrete scales of convective motions, ranging from the well-known granulation with cell diameters of $2 \times 10^3$ km to supergranulation at $30 \times 10^3$ km, with a newly discovered, but much weaker, intermediate-scale velocity pattern called mesogranulation. These motions appear not to represent fully developed turbulence with a smooth spectrum of kinetic energy. A fundamental issue in solar physics is to determine how such a discrete distribution of scales arise. One theory is that the depths of the hydrogen and helium ionization zones lead to particular scales of cellular convection which are especially efficient at extracting energy from the unstable stratification; but this speculation has not been proven.

To resolve the issue we must perform three-dimensional compressible convection simulations with a broad spectrum of resolved spatial scales and realistic equations of state. It is likely that the simulations will have to span horizontal scales from about $10^5$ to $10^6$ or even $10^7$ km, with the smallest scale located in the inertial subrange of the turbulence. The actual dissipation range will have to be parameterized, for it may well peak at scales of $0.1$ km or less; however, it is likely that the energy-containing scales will not be overly sensitive to the details of the subgrid parameterization provided a portion of the inertial subrange is analyzed in detail. Revising the vertical structure presents comparable challenges because the density scale height decreases from about $10^4$ km at the depth of He$^{++}$ ionization to about $200$ km at the surface.

Definitive simulations of the moderate and small scales of convection in the sun are likely to require at a minimum $128^3$ spatial elements, using a highly stretched vertical mesh and spectral representations in the horizontal. The $128^3$ estimate is a lower bound at best, given the $10^4$ contrast in the horizontal scales of solar convection that must be resolved, for even with such a model, the spatial spectrum will be sparsely sampled. Further, adequate resolution in the vertical may well require 512 discrete elements. Thus there would be a total of $8.4 \times 10^6$ discrete spatial elements in three dimensions. Depending on the formulation, seven to ten independent physical variables must be determined at each grid point (spatial or spectral) for the hydrodynamics alone if the radiative transfer is treated just within the diffusion
approximation. Proper radiative transfer analysis at the solar surface will very significantly complicate the numerical representation. A relatively simple $128^3$ compressible-convection time evolution is likely to require computer resources equal to 20 to 40 hours of CRAY-1A central-processing-unit time to produce meaningful statistics. Calculations with $512^3$ resolution, unattainable on a CRAY-1A-class machine, will probably be required to disentangle the spectral character of turbulence in the sun. For them, an AVC is clearly required.

Flux Tubes and Sunspots

The sun's magnetic field spans at least as broad a range of spatial scales as its motion fields, but, by contrast, is highly intermittent. At the sun's surface, the basic magnetic element is the isolated magnetic flux tube, containing a peak field strength of up to 2,000 gauss, but generally surrounded by a much larger, nearly field-free region. No more than one percent of the sun's surface is actually occupied by flux tubes at any one time. An individual flux tube is estimated to have a diameter of 100-200 km, somewhat below current telescopic resolution limits, and substantially smaller than even solar granules.

However, flux tubes are observed to group into patterns of much larger scale. Though polarities are generally mixed, very large areas typically have a measurable net magnetic polarity. These bipolar and unipolar magnetic regions, as they are called, evolve in a systematic fashion during the course of a solar cycle, with the net polarity of polar fields on the sun changing sign near the maximum of solar activity. In addition, sunspots, which are really closely packed aggre-gates of many flux tubes, show an arrangement of consistent magnetic polarity which is true of every group of spots in each hemisphere and each cycle, both reversing with successive cycles. Thus there is both a fundamental fine structure to the solar magnetic field and a systematic global ordering that evolves through the solar cycle. Here we discuss the modeling required to gain an understanding of the fine structures. We look at the solar cycle problem in the next section.

Modeling of magnetic flux tubes and their surroundings has been carried out with increasing sophistication over the past two decades. A number of relatively simple, even analytic, calculations have been done which illustrate how convection patterns will sweep initially diffuse field lines into the small regions of horizontal convergence of the flow to produce intense magnetic field concentrations. However, the models generally underpredict magnetic field strengths by a factor of four or so. It is now fairly clear that compressibility is crucial to explain the observed field strengths. The compressibility allows the partial evacuation of the inside of the flux tube, so it collapses until the magnetic pressure inside becomes an appreciable fraction of the ambient gas pressure. Conceptual and partially quantitative models of this process exist, but no detailed nonlinear calculations, following the evolution to a final equilibrium state, have been attempted. Such calculations are essential if we are to understand in a quantitative way the real interaction between the highly nonuniform magnetic field and the highly compressible convection surrounding it. The spatial resolution
needed for such a calculation would be similar to that described in the discussion on small-scale convection. Here, too, treatment of the smallest scales must be handled carefully, with guidance from theories and models of magnetohydrodynamic turbulence, because the magnetic dissipation scale on the sun is much smaller than even the flux tube scale.

Success in detailed modeling of the interaction of flux tubes and convection at the sun's surface should help us infer the nature of the interaction deeper in the convection zone where it cannot be observed directly. For example, we do not know whether the magnetic field of the sun is as intermittent below as it is at the surface, and this is crucial for building an understanding of the solar dynamo. There are indications from dynamo theory, as now applied to the sun, that the magnitude of the interaction actually occurring between magnetic fields and flow is much less than theory predicts.

Since the discovery of decreases in luminosity associated with passage of sunspots across the solar disk, detailed dynamical modeling of sunspots now assumes a particularly important role. Of special interest is the question of how, how long, and in what form the convection zone stores the energy blocked out by the spot. Relatively simple models exist, but these assume the form of most important processes involved, rather than calculating them explicitly in a self-consistent manner. A number of different flow patterns have been postulated in the neighborhood of spots in order to account, for example, for the deficit in heat flux seen there, but none of these have actually been predicted from nonlinear dynamical calculations in which several different physical effects are allowed to compete.

What is needed is development of detailed dynamical models of a sunspot and surrounding convection. Models for an axisymmetric spot and surrounding convection would be quite feasible, even on a CRAY-1A, but full three-dimensional calculations predicting the growth and evolution of a "typical" spot require the speed and memory of an AV. This area of modeling is relatively undeveloped, and a hierarchy of models of increasing complexity, each built on understanding gained from simpler versions, is probably the most appropriate strategy to follow in the next several years.

The Solar Cycle

The solar cycle is the most prominent and revealing form of solar variability, and most solar structures and output (radiation, magnetic fields, and flows of energetic particles) change with phase during the cycle. The current aim of several solar physics groups is to understand the basic workings of a single cycle, and to answer such questions as: What causes the rise and fall of sunspot numbers and active regions, and the systematic migration of active region appearance toward low latitudes as the cycle progresses? What causes the migration of fields toward the poles to reverse the polar fields near cycle maximum? What keeps cycles in the northern and southern hemispheres nearly in phase, but allows virtually no sunspots to cross the equator?
In addition, it is necessary to understand why successive solar cycles often do not have the same amplitude or period. The resulting undulations in the envelope of solar cycles also need to be understood. The existence of even more extreme behavior, such as the so called "Maunder minimum," a period of 70 years when cycles and sunspots almost disappeared, remains a puzzle.

Progress has been made over the past 15 years with relatively simple, linear dynamo models that appear to explain many features of the solar cycle. However, this progress constitutes only a beginning, since the relatively large number of free parameters in these models allow rather close "fitting" to the observed cycle, without much independent, physically based justification for the parameter choices. One reason for the free parameters is that these dynamos were essentially kinematic; that is, only the induction equation is solved, not the full equations governing the fluid dynamics and magnetohydrodynamics. Both convection and the observed latitudinal differential rotation of the sun play profound roles in the dynamo, and are themselves closely coupled together by the laws governing fluid dynamics. Nevertheless, kinematic dynamo models assure that convection and differential rotation amplitudes and profiles can be chosen independently. Partly because of computer limitations, the full problem has only recently begun to be attacked, starting from a self-consistent calculation of convection and the differential rotation it drives, in a rotating spherical shell corresponding to the solar convection zone.

Recent results from such modeling indicate there is much more to be done before we can gain a real understanding of the solar cycle. For example, a recent calculation for a convectively driven dynamo, in which convection drives differential rotation of the observed solar amplitude and surface profile, gives dynamo periods which are too short for the sun by a factor of ten, with the toroidal fields migrating toward the poles with time, rather than toward the equator as seen on the sun. This model is quite simple physically compared to the real sun, but contains much more of the relevant physics than the kinematic models.

It appears that lack of compressibility in the model may be responsible for the incorrect direction of migration of toroidal fields. The inclusion of compressibility in the form of a radial variation in fluid density that varies by a factor of \(10\) to \(10^3\) in the solar convection zone will substantially add to the computational requirements. The short dynamo period may be due to inaccurate representation of the interaction between the small-scale velocity and magnetic fields. Remedying this problem will probably require both substantial calculations of nonlinear magnetohydrodynamic turbulence and more sophisticated (and computationally expensive) parameterization schemes for small scales. It is important to capture the known intermittency of the sun's magnetic field in the models, and no one has really done so yet. Despite these difficulties, the current generation models are addressing the nature of the feedbacks of induced magnetic fields on the flow, which is crucial if we are to understand how the sun's magnetic cycle is bounded and modulated.
The basic computational limitation on current solar dynamo calculations is that simulating even one full magnetic cycle requires many time steps. With the current model, one magnetic cycle requires about eight hours of CRAY-1A time, and that corresponds to only about two years of simulated solar time, a small fraction of the 22 years of a real solar magnetic cycle. As we identify the processes that must be present to slow the model’s cycle time so that it corresponds to that of the sun itself, the simulations of the cycle will consume an order of magnitude more computer time, since these processes occur on space scales substantially smaller than those currently resolved in dynamo models. Thus any systematic study of nonlinear convectively driven dynamos which produce cycles similar in length of that of the sun will require an AVC.

Astrophysical Radiation Hydrodynamics

Radiation plays at least three fundamental roles in astrophysical fluid dynamics: It provides the diagnostics from which we infer the physical structure of the fluid and the flow, it determines the distribution of particles over available excitation and ionization states, and it can drive the fluid flow.

In what follows we evaluate the present status of, and future prognosis for, some representative aspects of each of these roles from the point of view of computational tractability with present-day and presently foreseeable computers.

The ultimate goal in the diagnostic problem is to infer from the radiation field the temperature, pressure, density, and velocity of the material (and magnetic fields if we measure polarized radiation) as well as the detailed distribution of atoms over their excitation and ionization states. With respect to velocity fields, it is necessary to establish the presence of flows of many types, including convection, turbulence, waves and oscillations, pulsations, and winds (global expansions) and to determine the response of the atmosphere to these flows. To do this we must rely on information derived from an analysis of the observed spectrum, in situ measurements being possible only in the interplanetary medium and rare even in that region.

The diagnostic problem is extremely complex because the final spectrum we measure is the result of a complicated ensemble of highly nonlinear phenomena. Moreover, the solar layers observable by us are precisely those from which photons escape freely, and within which photon exchange can occur efficiently within a large interaction volume whose size is set by the destruction length for photons as they scatter repeatedly through the medium. This kind of exchange makes the problem severely nonlocal, since the state of the material at one point in the medium becomes coupled to (and, reciprocally, reacts back upon) the state of the material at many other, perhaps remote, points in the medium. Thus we must confront the so-called non-LTE (nonlocal thermodynamic equilibrium) problem, whose basic characteristic is that the state of the
material determines the radiation field via photon emissions and absorptions, but this state is simultaneously determined by the radiation field (a nonlocal quantity) through the rates of radiative excitation and deexcitation.

Ideally one would like to be able to calculate the radiation field from realistic flow models for a full atomic transition array. While great strides have been made on such problems in the past decade, we are still far from the goal just stated, and are unlikely to achieve it without major increments in computing power. With the CDC 7600 it was possible to develop important basic numerical techniques, and to perform somewhat idealized multilevel, multiline non-LTE diagnostic computations for one-dimensional media. For two-dimensional media it proved barely possible to handle even highly schematic two-level-atom (i.e., one spectral line) problems in terribly oversimplified caricatures of physically interesting structures in the solar atmosphere (e.g., prominences, convection cells).

With the advent of the CRAY-1A, multilevel calculations for one-dimensional static media have become routine, and current efforts are devoted to improving the representation of the physics (e.g., allowing for the effects of partial redistribution). A parallel thrust is to begin modeling one-dimensional media with given velocity fields; these computations are probably within grasp (though costly) on a CRAY-1A, and should provide valuable "snapshots" of the diagnostics for a few characteristic times in a flow. It is, however, not feasible, except with an AVC, to provide full diagnostic information at each time step of a dynamical calculation that may run for, say, thousands or tens of thousands of time steps. For two-dimensional media, using the CRAY-1A should make it possible to at least begin treating multilevel problems, though both the data management and pure number-crunching capabilities of the machine will be taxed heavily; a satisfactory treatment of realistic models is probably beyond reach until the AVC is available.

With the availability of machines having order-of-magnitude larger numerical throughput and storage than the CRAY-1A, several major advances become possible. For one-dimensional media it becomes possible to compute realistic (i.e., multi-line, multilevel) spectra for arbitrary flow fields sufficiently rapidly to follow the full time evolution of the spectrum on dynamical time scales. Thus it would be possible, for example, to model time-dependent spectra of astrophysically important atoms and ions (e.g., H, Mg+, Ca+, Fe) in a pulsating variable star, and to obtain, for the first time, theoretical spectra to compare with both visible (available for over two decades) and ultraviolet (currently becoming available from space observations) data. One anticipates major and fundamental improvements in our understanding of shock propagation in stratified radiating fluids from such studies. Likewise it should be possible to model spectra from explosive events such as solar flares. In two-dimensional media the calculation of realistic spectra in the "snapshot" mode described above will become feasible. (However,
following the full time-evolution of a realistic spectrum in a multidimensional structure will remain beyond reach for reasonable real-time investment on the part of the scientist even with an AVC and must await some future computer development.

The present state of modeling the dynamics of radiating flows is primitive. With machines in the CDC 7600 class it is possible to handle (though slowly) the dynamics of, say, a pulsating variable star provided that one makes two severely simplifying assumptions: (1) the material is in LTE, and (2) the radiation is treated in the diffusion approximation. If one attempts to do realistic transport, the calculation becomes prohibitively slow in terms of the scientist's real time except for a few demonstration-type problems. If one removes the assumption of LTE the problem becomes so costly in computer time that only two highly schematic calculations of the propagation of a single shock in a stratified atmosphere have ever been performed.

With machines in the CRAY-IA class it is possible to calculate full dynamical models of one-dimensional LTE flows (e.g., pulsation) with genuine radiation transport on a fairly routine basis. In two dimensions, a radiation hydrodynamics calculation with full radiative transport, even in LTE, has never been attempted, and doing so would be at the edge of CRAY-IA capabilities for acceptable running times. Exploratory studies of the feasibility of doing so have only begun. With a CRAY-IA, one-dimensional dynamical models with non-LTE transport appear marginally feasible. It is likely that departures from equilibrium in continua can be handled for multilevel atoms in time-dependent flows; the treatment of lines, however, remains open to question. At present only extremely rough calculations based on heuristic probabilistic formulations of unknown accuracy have been attempted. Currently available computer power makes the outlook for "rigorous" treatments of the problem appear very pessimistic.

On the other hand, with an AVC, LTE transport coupled to the dynamics in two-dimensional flows becomes practical, and the limiting factor in our progress is likely to be the development of robust algorithms. Similarly, for one-dimensional flows the treatment of nonequilibrium transport, including at least a few spectrum lines, begins to look feasible. Such calculations can revolutionize our present understanding of the coupling between radiation and fluid dynamics, and of the energy and momentum exchange between the thermal reservoir and photons, in a very wide variety of problems crucial to astrophysics and solar physics. We appear to be at the threshold of constructing a relatively consistent physical (theoretical) description of the coupled dynamical and diagnostic problems, and of arriving at the points where we can handle nonequilibrium phenomena in the flow sufficiently well to produce models that accurately simulate reality and which provide reliable and sensitive diagnostic tools.
Estimates of Resources Required for Major Problems

The following table summarizes requirements for Class VI and Class VII computing power for each of the problem areas discussed above:

<table>
<thead>
<tr>
<th>CRAY-1A Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-scale solar convection</td>
</tr>
<tr>
<td>Flux tubes and Sunspots</td>
</tr>
<tr>
<td>Solar Cycle</td>
</tr>
<tr>
<td>Astrophysical radiation hydrodynamics</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
</tr>
</tbody>
</table>

Additional resources will be required by scientists working in other solar and interplanetary research areas.
TURBULENCE THEORY

(Drafted by Steven Orszag, Massachusetts Institute of Technology, in consultation with Jackson Herring, NCAR, and Uriel Frisch, Nice Observatory.)

There is virtually no fluid dynamical process in the terrestrial or solar atmosphere or in the ocean that does not involve turbulence, whether the motions are on scales of millimeters or millions of kilometers. For many of the most important and critical dynamical problems, research progress is limited by the state of our knowledge of turbulence. This is particularly true of efforts to model atmospheric processes.

In all fluids, including air, water, and solar gases, the most important physical consequence of turbulence is the enhancement of processes that transport momentum, energy and particles from one location to another.

The fundamental characteristic of turbulent flows that makes them so theoretically and computationally difficult is that they exhibit much more small-scale structure than their nonturbulent counterparts. In fact, this small-scale structure is correlated with enhanced turbulent transport phenomena. Small-scale structure itself is evidence of enhanced transport in the sense that small scales develop from the degradation of large-scale excitations that are maintained by energy transport from one scale to another. Thus the fundamental difficulties of the turbulence problem, are, excitations extending over a huge range of scales, together with the central role of nonlinearity in mediating interactions among these scales.

Another important characteristic of turbulent flows is their apparent randomness and instability in the face of small perturbations, a feature noticeable in nearly every atmospheric and oceanic process. Two turbulent flows that are at some time nearly identical in detail do not remain nearly identical on the time scales of dynamical interest. Instability of turbulent motion is related to the limited predictability of atmospheric motions. The character of the onset of this randomness, i.e., the transition to turbulence, is a subject of much current interest and involves the study of such complicated dynamical phenomena as those of "strange attractors."

It has become clear over the past decade that in order to make substantial progress in our understanding of turbulent flows, we must bring to bear the largest and most powerful computer resources available. Several kinds of computer studies are important including:

- Full numerical solution of the Navier-Stokes equations for turbulent flows to answer fundamental fluid dynamical questions
- Numerical tests of analytical theories of turbulence
- Numerical tests of turbulent transport approximations for use in large-scale computer models of the atmosphere
• Studies of the origin of turbulence, including investigations of possible routes leading to chaos (apparent random behavior).

Recent History of Turbulence Computations

NCAR's computing capabilities have been involved in many major advances in the computational state of the art for turbulence problems. The first numerical simulations of two-dimensional turbulence were performed with NCAR computers by Lilly in 1969; the first numerical simulations of three-dimensional turbulence were performed by Orszag and Patterson in 1971; the first large-eddy simulation of shear turbulence was performed by Deardorff in 1970; and the first large-eddy simulation of turbulence in a stratified shear flow was performed by Deardorff in 1972. As discussed below, many more recent accomplishments continue this tradition.

It is evident from recent history that increased computing power can stimulate new ideas of how to attack various problems. Unfortunately, this phenomenon is unpredictable. Nonetheless we can predict to an extent the resources that will be needed in the coming decade for vigorous pursuit of the central problems of turbulence theory. Because scientific opportunities often present themselves unexpectedly, the estimates given in this section should be considered conservative.

First, let us turn the clock back to 1975, before the introduction of the CRAY-1A computer, and describe the state of the art at that time. Then we shall describe what has been done in the intervening seven years. In this way it will be possible to provide a reasonable picture of the kinds of developments that should be expected through the late 1980s.

In 1975 the state of the art involved full numerical solutions of the Navier-Stokes equations with up to 32 x 32 x 32 degrees of freedom in three space dimensions and 128 x 128 degrees of freedom in two dimensions. Low-Reynolds-number inertial-range dynamics was already studied in two dimensions, but the study of three-dimensional inertial-range dynamics seemed well beyond the power of computers through the end of this century. Numerical studies of thermal convection in two dimensions had been done, as well as some isolated, low-resolution, three-dimensional convection studies. However, there were no systematic studies of the origin of chaotic time-dependence in flows, nor was it clear then that numerical methods would prove decisive in understanding the transition to turbulence. Large-eddy simulations were well on their way, given the pioneering work by Deardorff at NCAR; but there were no attempts at that time to use the computer to understand the basic fluid dynamics of wall layers in turbulent shear flows. Thus in 1975 computations of turbulence that took into account all relevant scales of motion was only in its infancy, and scientists were just beginning to
perceive the usefulness of such methods in providing answers to fundamental fluid dynamical questions.

With the advent of the CRAY-1A at NCAR in 1978, studies could be done using computer codes with an order of magnitude more resolution than possible with the Control Data 7600. Some significant accomplishments include:

1. **Taylor-Green vortex and three-dimensional inertial-range dynamics.** New algorithms have been developed that allow the numerical solution of a prototype three-dimensional vortex motion, called the Taylor-Green vortex, with up to 512 x 512 x 512 spatial resolution on the CRAY-1A. Thus it has been possible to achieve an order-of-magnitude improvement in spatial resolution over the old 32 x 32 x 32 codes used in the earlier three-dimensional turbulence simulations. While the Taylor-Green vortex is a rather special flow, it is not believed that the special symmetries characterizing this flow restrict significantly the small-scale dynamics of the inertial range. Indeed, the simulations have permitted the first direct, even though crude, calculation of a Kolmogorov-like three-dimension-1 spectrum. In addition, these calculations have permitted the study of intermittency effects on the dissipation-fluctuation spectrum. These studies are connected with very fundamental questions concerning the nonlinear fluid dynamics of incompressible flows. In particular, the Taylor-Green vortex has been used to study the question of whether frictionless (inviscid) flows can stretch vorticity an infinite amount in a finite time. The resolution of the existence of this singularity for the inviscid Euler equations in three dimensions remains undecided at the present time, but essential new insights into the dynamics of three-dimensional flows have been obtained by these numerical studies.

2. **Turbulent magnetohydrodynamics (MHD).** Over the past three years, Frisch and his collaborators have made a number of elaborate computations of nonlinear MHD dynamos whose purpose was to understand how magnetic fields are generated in moving conductors (e.g., the solar and terrestrial dynamos). Three-dimensionality is a well-known prerequisite for such dynamo effects; furthermore, since magnetic Reynolds numbers tend to be on the order ten or larger, reliable calculations require the highest resolutions which can be employed on the CRAY-1A (64 x 64 x 64). However, more realistic three-dimensional modeling of natural phenomena will require larger computers in order to include more than one dominant physical effect, a nontrivial geometry, or the exploration of a wide region of parameter space.

3. **Large-eddy simulations and the renormalization group.** Recently, it has proved possible to carry the renormalization group ideas from field theory to high-Reynolds-number fluid dynamics. In this way, it has been possible to "derive" modified formulations of small-scale eddy viscosities for use in large-eddy simulations of turbulent flows. Experimentation with these ideas has just begun on the NCAR CRAY-1A. However, it is hoped that these ideas may lead to significant advances in our ability to model the effect of small-scale turbulent motions accurately.
4. **Small-eddy simulations.** Siggia of Cornell has suggested the study of small-scale turbulence dynamics by eliminating the large eddies. In this way, the range of effective scales is reduced and the cascade process can be studied independently, of peculiarities of the large scales.

5. **Transition to turbulence in wall-bounded shear flows.** Careful analysis of the results of direct numerical simulations of the transition to turbulence in wall-bounded shear flows has suggested a very simple mechanism for transition in these flows. Thus, it has been possible to isolate a three-dimensional instability which obtains in these flows and which has many of the characteristics of experimentally observed transitions. In particular, the new instability seems to explain the critical Reynolds numbers for the onset of turbulence as well as many of the spatial characteristics of these flows.

Interestingly, we have discovered that transition calculations can be performed with much less spatial resolution than turbulence calculations, but they require considerably more time resolution. The reason is that it takes a long time for the weak nonlinear interactions present in a flow undergoing transition to affect the character of the flow. Typically, transition calculations require one to two orders of magnitude more time steps than turbulence calculations require.

6. **Convection flows.** Over the past few years, it has proved possible to investigate numerically the routes to chaos in thermally convection flows. In contrast to the classical Landau picture of transition, in which an infinite number of degrees of freedom must be excited before broad spectral response and turbulence are obtained, numerical simulations have verified the more recent Ruelle-Takens-Newhouse picture, in which chaos obtains after three Hopf bifurcations occur. Again it is necessary to integrate for very long intervals of time in order to analyze the time-frequency spectrum of the flows properly. The character of strange attractors in convection flows has been elucidated numerically, including results such as the difference between two- and three-dimensional attractors. Again, it is clear that considerably more computer power will be required in order to integrate long enough in time to distinguish between scenarios that differ in very subtle ways. On the CRAY-1A, the highest-resolution convection calculations have used $32 \times 32 \times 32$ spatial resolution. Resolution at least a factor of two higher is required to settle important outstanding questions.

7. **Wall-bounded turbulence.** With homogeneous turbulence, it is possible to obtain some crude results with $16 \times 16 \times 16$ resolution, while good moderate-Reynolds-number results are obtained at $32 \times 32 \times 32$ resolution. On the other hand, with inhomogeneous turbulent flows, such as those bounded by walls, $32 \times 32 \times 32$ spatial resolution is only marginally accurate; $64 \times 64 \times 64$ spatial resolution seems required to obtain reliable results. The latter resolution has been possible only
of the CRAY-1A at NCAR. It has now proved possible to solve the Navier-Stokes equations for such shear flows directly and to predict the characteristics of these flows numerically. In particular, it has proved possible to simulate a logarithmic layer whose Karman constant is well within experimental bounds.

8. Free shear flows. The numerical study of turbulent free shear flows is of interest in understanding both atmospheric jets and such topics as clear air turbulence. Recently, numerical results have clarified the role of three-dimensional instabilities in these flows as well as pairing-vortex instabilities. In this way, the essentially two-dimensional character of these flows has been clarified with respect to their small-scale turbulence structure.

9. Numerical studies of analytical turbulence theories. Over the past ten years, Herring, Leith, and others have developed numerical techniques for the accurate and efficient solution of the equations of such analytical turbulence theories as the direct-interaction approximation and the test-field model. These theories have proved particularly useful in the analysis of such problems as the predictability of atmospheric motion and rotating, strongly stratified turbulence. The power of the supercomputers is particularly important outside the regime of homogeneous, isotropic turbulence. Initial studies of axisymmetric, homogeneous turbulence using analytical theories have been done, but they tax the power of even the largest computers. The eventual goal of these studies is to simplify the analytical theories sufficiently that this high computation can be significantly reduced, but doing this will require a large number of detailed numerical studies of the analytical theories over a period of at least several years.

A Forecast of Problems to Be Solved on Advanced Vector-Class Computers

In this section, we give a survey of some problems that will probably be possible to solve on the next generation of computers. We also include estimates of the computing power necessary to solve these problems. A summary of estimates of computing time required is given at the end of this section.

1. Small-scale structure of turbulent flows. The direct numerical simulation of inertial-range dynamics in multidimensional turbulent flows will tax both the memory and the speed of the next generation of computers. It is essential to have the largest possible range of scales included in the calculations in order to isolate the physics of the generation of small scales. One approach would be to extend our current Taylor-Green vortex calculations to $1,024 \times 1,024 \times 1,024$ spatial resolution. The importance of doing this is that the results obtained on the CRAY-1A are accurate until just slightly before the putative singularity of the Euler equations. With the higher resolution it should be possible to determine whether or not such a singularity exists. In addition, it should be possible to study in detail small regions of the flow in which very strong vortex stretching is occurring. In particular, the differences between viscous and inviscid flows should be studied in
detail. It seems now that viscosity may be necessary to break the topology of vortex lines and hence permit the generation of fully developed turbulence. In this case, there can be a back cascade of information from the smallest scales (on which vorticity acts) to macroscopic energy-containing scales.

In addition to further studies of specialized flows like the Taylor-Green vortex, it is necessary to pursue studies of general turbulent flows (without symmetries and other special properties). On Class VII computers, it should be possible to perform routine computations at 128 x 128 x 128 or possibly even 256 x 256 x 256 resolution.

2. Turbulent shear flows. With an order-of-magnitude increase in both computing speed and memory, it will be possible to study turbulent shear flows in complex geometries and with complicated physics. Thus, it should be possible to study turbulent flows with orography, complicated inflow-outflow boundary conditions, multispecies physics, etc. As mentioned above, spectral resolution of at least 64 is required to do a good job of simulating turbulent shear flows at moderate Reynolds numbers. On the CRAY-1A computer, a typical run at 64 x 64 x 64 resolution requires ten to 20 hours of computer time; on the next generation of machines, this run should be possible in about 1 h, which means that significant exploration of physics can take place. State-of-the-art computations should be done on the next generation of machines with 128 x 128 x 128 spatial resolution and will also require a minimum of about 20 h per run.

3. Large-eddy simulations. It is important to explore the range of utility of new ideas on renormalization group methods in fluid dynamics. In particular, one class of computations that will require the power of Class VII machines is the use of nested grids to resolve the wall layers of turbulent flows. With classical subgrid-scale ideas, the smallest resolved feature of a turbulent shear flow in the neighborhood of walls, namely the streaks, is essentially the smallest-scale structure in the flow. Therefore, if one uses large-eddy simulation ideas up to and including the wall, there is very little difference in the required resolution of the subgrid-scale model and a full numerical solution of the Navier-Stokes equations at the specified Reynolds number. In other words, large-eddy simulation buys very little in the way of spatial resolution unless one models the wall layers and does not calculate through them. On the other hand, with renormalization group ideas, it is possible to use a nested-grid approach to the wall layer, and hence reduce the required resolution significantly. Such computer codes will be extremely complicated and will require the largest available resources.

4. Two-dimensional turbulence. The large capacity of Class VII computers will be necessary to resolve the inertial ranges of two-dimensional turbulence properly. In particular, it should be possible to investigate the inverse two-dimensional energy cascade as well as the forward two-dimensional enstrophy cascade. On these machines, it will be possible to use resolutions of up to 2,048 x 2,048
(without symmetries), so a healthy separation of scales will be feasible. Studies of two-dimensional stratified turbulence, in particular the interaction of internal waves with turbulence, will then be possible. The effect of turbulence on mesoscale wave dynamics may be particularly significant in atmospheric dynamics and is a problem where it seems to be particularly important to retain a large range of scales.

5. Shear turbulence. The improved computing power of Class VII machines will make possible the study of interactions between internal waves and shear flows. In particular, it should be possible to study the extraction of energy by clear air turbulence, as well as the structure of a possible inverse-5/3-power spectral range.

6. Transition problems. As emphasized above, transition studies require only moderate spatial resolution, but they do require a very large number of time steps, so the required computing resource is not at all small. On Class VII machines, current state-of-the-art computations will become routine, so it will be possible to investigate much more complicated phenomena. It now seems that accurate transition calculations of moderate- to high-Prandtl-number thermal convection will require at least 64 x 64 x 32 spatial resolution. With 50,000 time steps per run, this would require at least 70 h per run on a Class VI machine. With the increased computing power of Class VII machines, it will be possible to catalogue the possible transitions in both two- and three-dimensional convecting flows with a wide variety of boundary conditions.

At the present time, it can be confidently said that our ability to calculate transitional flows on the computer will, within the next few years, closely rival the ability of experimentalists to extract useful information about these flows in the laboratory. Thus, this research area provides a bridge between modern thinking in mathematics (strange attractors, dynamical systems) and such important atmospheric questions as climate modeling, Gulf Stream meandering, and so on. (Even though the latter flows are basically turbulent in character, the chaos exhibited by them may best be approached via transitional ideas.)

7. Magnetohydrodynamic flows. As mentioned above, dynamo calculations require at least 64 x 64 x 64 spatial resolution, which are particularly difficult on the CRAY-1A because of its limited fast memory. The advent of Class VII machines will mean that these computations can be done routinely and a large region of parameter space can be explored. Thus, it is reasonable to expect that there will be significant advances over the next five years in our understanding of solar and terrestrial dynamos.

8. Quasi-geostrophic turbulence. Since we have now just begun to get good calculations of inertial range dynamics using the CRAY-1A computer, it is reasonable to expect that such calculations will be possible for flows like quasi-geostrophic turbulence, rotating turbulence, etc.
9. **Analytical theories of turbulence.** The numerical solution of the equations of analytical turbulence theories, like the direct-interaction approximation for inhomogeneous, anisotropic flows, is an exceedingly large task. The problem has not been completed on the current generation of machines because they are not large or powerful enough. On the next-generation machines, it is reasonable to expect that the first fundamental calculations of shear flows using these theories will be done.

**Summary and Estimates of Computational Needs**

Von Neumann's 1949 prediction that computers would prove particularly useful for the study of turbulent flows has now become true. Because of the still very poor theoretical understanding of nonlinear phenomena, atmospheric scientists, astrophysicists, fluid dynamicists, and others are in great need of computer simulations. To continue recent advances in many aspects of the study of turbulence, the computer power and memory of a Class VII machine are required. In basic research, the need for such capabilities will continue at least until we can achieve resolutions in which the asymptotic regimes are manifest (probably never less than 256 x 256 x 256 resolution and often much more, depending on the problem).

The table below shows the number of hours of central processor time on a Class VII machine that will be required annually for each of the problem areas just discussed. Also shown are the number of CRAY-1A hours that would be equivalent. The CRAY-1A figures are presented only to provide comparability with other sections of this chapter; it should be emphasized that a CRAY-1A is severely limited in dealing with this class of problems. Not only is the CRAY-1A's memory too small, but also such long runs would be required on the CRAY-1A that elaborate programming routines would be necessary, in order to cope with any interruptions in the run. Until a Class VII machine is available, work on the problems described in this section will be severely inhibited and progress will be significantly less than is warranted by the importance of these problems to atmospheric, oceanic and solar dynamics.

<table>
<thead>
<tr>
<th>Class VII Central Processing Unit</th>
<th>Equivalent CRAY-1A Hours/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU Hours/Year</td>
<td></td>
</tr>
<tr>
<td>1. <strong>Small-scale (inertial-range)</strong> turbulent structure calculations (two- and three-dimensional)</td>
<td>200</td>
</tr>
<tr>
<td>2. <strong>Large-eddy and renormalization group studies</strong></td>
<td>125</td>
</tr>
<tr>
<td>3. <strong>Wall-bounded turbulence studies</strong></td>
<td>125</td>
</tr>
</tbody>
</table>
4. Free (stratified) shear flow turbulence (internal waves) studies  & 175 & 875  
5. Quasi-geostrophic and rotating turbulence & 100 & 500  
6. MHD turbulence and dynamos & 100 & 500  
7. Shear flow transition studies & 75 & 375  
8. Convection and MHD convection & 100 & 500  
9. Analytical theories, especially for inhomogeneous, anisotropic flows & 75 & 375  

**TOTAL** & **1,075** & **5,375**

Thus, approximately 15 percent of an Advanced Vector Computer, as a conservative estimate, should be usefully applied to these fundamental problems.
SCIENTIFIC DATA PROCESSING

(Drafted by Roy L. Jenne, NCAR, in consultation with scientists from NCAR and other institutions.)

The purpose of this section is to provide a guide for determining the kinds and magnitude of data processing tasks that can most easily and economically be done on Class VI or Class VII computers.

To develop a rationale for determining what data processing makes sense on a fast machine, this section first discusses data flow rates in a fast computer for different levels of memory. Then we will compare the CPU time needed for selected data processing tasks to the time needed to obtain data from archives. The comparison indicates that many tasks are most effectively done on fast machines. Data channel rates will increase. This will permit the processing of data with less time delay and cost if higher CPU speeds are available.

Next, in order to examine the amount of data processing on fast machines at NCAR, we describe the data flow to and from the mass store and the size of the archive. Then selected data archives and data processing projects are briefly described as examples of what data processing has been done, and what will be done in the future. For example, to process climate model output, it is expected that over 500 hours of CRAY-1A CPU time per year will be required.

Information Flow in Computing Systems

With a machine like the CRAY-1A, which makes calculations at rates of about 70 MIPS (or 20 megaflops - useful adds, multiples, etc.), the data flow between memory and calculation registers is at rates of about 3900 megabits per second. Fortunately, this total data flow doesn't have to be saved, but only selected results. For many large models, the total grid point array cannot fit into the main (expensive) memory. Therefore, at any one time many of the grid points must be on fast disks. Each 36 megabit/sec disk channel has an effective rate of nearly 17 megabits. With 4 channels, the effective total disk rate can be up to about 66 megabits. It is also fortunate that this total disk data rate doesn't have to be saved. In the typical model, only a small percentage of the time steps are saved, and perhaps the space resolution is truncated, and the numbers packed into fewer bits forarchiving. At NCAR we will see that the average rate of data flow to and from the mass store and tapes now is about 1 megabit.

Data Processing

While all computing is actually data processing, we generally reserve that term to mean the processing of data that must be moved to and from archive devices such as tapes and mass store, or data from real time input channels. This includes model results and observed data from conventional sources and space satellite systems. The question is how much of the total data processing load is accomplished at least cost on a fast computer such as Class VI or VII machines. The problem with doing certain easy tasks (such as a tape copy) on a very fast computer is that this may tie up some of the disk
channels that are needed to keep other jobs going at full speed. To determine what data tasks are done best on a fast machine, one must obtain the processing time needed per unit of data, and compare this to the time needed to move data. Table 5 gives the time needed for selected computational tasks. This should be compared to the time needed to move data from archive devices, as given in Table 6. It is clear that many data tasks make effective use of the computational power of a fast computer. Since the unit cost of a calculation is typically less on the fast machine, the task is then also done with less expense.

When comparing the calculation times and data rates in Tables 5 and 6, we must also recognize that several I/O channels are usually active at once to feed only one or two central processors (CPU's). In fact, the objective is to choose a hardware configuration that balances the channel bandwidth and the compute power according to the tasks expected in the job mix. An installation that needs to move much data to and from the outer world needs more channel bandwidth than a computer with a low data flow. To measure the utilization of computing power at NCAR, we especially monitor the hours the CPU is busy compared to the total available hours. For individual jobs we also look at the ratio of channel time to CPU time. For data jobs that were mostly light computing and data selection, the ratio on the Control Data 7600 was often about 4 or 5 to 1. When the 7600 was the primary computer being used, the overall ratio for all jobs was about 1 to 1. This says that the I/O channels were somewhat under-utilized because there were several channels and only one CPU.

The data rates of archive channels also have increased with time. Table 6 shows that tape channel rates went from .5 megabit to 10 megabits from 1960 to 1981. In the next several years, increases in mass store data rates by factors of 5 to 10 are also expected. For these higher data rates, a faster computer is needed to keep up. It is like drinking water from a fire hose; you have to swallow pretty fast. At NCAR we have found that one should be cautious of traditional front-ending concepts in which all data to the fast machine flows through the front-end. For the high-rate channels, this concept can lead to bottlenecks in the flow of data to the fast machine, and it detracts from other tasks that the front-end could do. Smaller machines, such as VAX-class computers, cannot cope in a timely way with the high flow rates and very large amounts of data being discussed here. Moreover, economics of scale enter into the choice of the faster machines in an important way. (However, there are many effective roles for the slower machines. For example, to concentrate low rate data flows, to handle repetitious tasks that can be optimized without a lot of I/O equipment, for many control problems, and for short jobs and for many interactive tasks, they are typically excellent.)

CPU arithmetic, memory, and I/O equipment are all expensive in computing systems. The cost of the arithmetic is high enough that one should avoid having the CPU go idle because it cannot be fed data fast enough. Conversely, the cost of the disks and channels and mass storage devices are also high. If a slow computer cannot keep up with available data flow rates, it cannot make good use of its I/O equipment and that is often a dominating part of the cost of such systems. It is probable that the cost of logic will continue to drop relative to I/O hardware.
Table 5

Time needed to make selected calculations on input data. If processing a given type of data takes 50 sec of CPU time per $10^8$ bits, then processing $10^{12}$ bits will take 139 hours.

**CPU Time Needed For Processing Each $10^8$ Bits of Data**

<table>
<thead>
<tr>
<th>Step Description</th>
<th>CDC 6600</th>
<th>CDC 7600</th>
<th>CRAY-1A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Decode data with I4 format.</td>
<td>375 sec</td>
<td>75 sec</td>
<td>31 sec</td>
</tr>
<tr>
<td>2. Unpack data from 12 bit pack.</td>
<td>166</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>3. Calculate hydrostatic check on U.S. raobs.</td>
<td></td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>4. Calculate monthly statistics from packed raobs.</td>
<td></td>
<td></td>
<td>335</td>
</tr>
<tr>
<td>5. Do tape copy with analysis grid selection.</td>
<td></td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>6. Do coordinate transformation on radar data.</td>
<td></td>
<td></td>
<td>864</td>
</tr>
<tr>
<td>7. Run $5^0$ lat-lon GCM model on Cray-1A. Data goes to/from disk each time step.</td>
<td></td>
<td></td>
<td>3.2</td>
</tr>
</tbody>
</table>
Table 6
Time needed to transfer data. For different I/O devices, the time necessary to move 100 million bits of data is given. These times assume serial access to the data.

<table>
<thead>
<tr>
<th>Data Input Device</th>
<th>Assumed Speed Efficiency</th>
<th>Time Per 10^8 Bits</th>
<th>Year When Becomes Common</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card Reader, 1000 cards/min</td>
<td>1.</td>
<td>9,375 sec</td>
<td>1962</td>
</tr>
<tr>
<td>Telephone Line, 4800 bits/sec</td>
<td>1.</td>
<td>20,830</td>
<td></td>
</tr>
<tr>
<td>7 tr 556 BPI, 150 IPS Tape Drive (0.5 megabit/sec)</td>
<td>.70</td>
<td>285</td>
<td>1960</td>
</tr>
<tr>
<td>9 tr 800 BPI, 200 IPS Tape (1.3 megabit)</td>
<td>.70</td>
<td>111.6</td>
<td></td>
</tr>
<tr>
<td>9 tr 1600 BPI, 200 IPS Tape (2.6 megabit)</td>
<td>.70</td>
<td>55.8</td>
<td>1972</td>
</tr>
<tr>
<td>9 tr 6250 BPI, 100 IPS Tape (10 megabit)</td>
<td>.70</td>
<td>14.3</td>
<td>1981</td>
</tr>
<tr>
<td>TBM Mass Store to core, 5.4 megabit channels</td>
<td>.41</td>
<td>45.17</td>
<td>1975</td>
</tr>
<tr>
<td>Disk to Core, 36 megabit channel</td>
<td>.46</td>
<td>6.04</td>
<td></td>
</tr>
<tr>
<td>Future mass store</td>
<td>.6</td>
<td>6.7</td>
<td>E1985</td>
</tr>
<tr>
<td>25 megabit channel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mass Storage

To grasp the amount of data processing currently being done on the fast computers at NCAR, it is useful to examine the flow of data to and from the present mass store (Ampex TBM). The data flow from the mass store is about 5 times the data flow from tapes. Figure 1 shows that the TBM flow is now at an average rate of about $2.2 \times 10^{12}$ bits per month. For comparison, an average 1 megabit/second rate moves $2.64 \times 10^{12}$ bits per month. Until 1981, all mass store data had to pass through the CDC 7600 to get to the CRAY, a procedure that limited the productivity of the 7600 and did not provide the CRAY enough capacity to communicate with the TBM. Therefore, a direct channel was installed to link the CRAY and TBM. The amount of data on the mass store has also been growing rapidly. The data volume has increased parallel to the number of data volumes saved, shown in Figure 1. This curve is jagged because of a purge cycle every 3 months. The total archive has grown from $3.0 \times 10^{12}$ bits in January 1980 to $9.8 \times 10^{12}$ bits in September 1982. Currently there are a total of $5.56 \times 10^{12}$ bits, not counting backup duplicates. Only a portion of the data can be on-line on the TBM at any one time (now $6 \times 10^{11}$ bits). These mass storage capacities should be compared with the best "mass store" of 1965, a tape strip system (strips were like cards) with an on-line capacity of $3 \times 10^{9}$ bits.

Examples of Data Sets and Processing Tasks

In this section, some examples of major data processing and archiving tasks are given. This list omits major tasks such as aircraft data processing, satellite limb scanner data, and many smaller tasks which collectively have a large impact.

1. General Use Global Data Sets

The NCAR Data Support Section has over 200 data sets ranging from 10 years of twice daily S. Hemisphere analyses from Australia, to observations, and various supporting sets such as elevation, ocean depth, and gas absorption line data. Many data sets will fit on one or several 1600 BPI tapes (300 million bits each), but a number are much larger. These sets are frequently used by university and NCAR scientists. The size of several of the larger sets is given in Table 7.
TOTAL VSNs ON THE TMS-4 SYSTEM AND TOTAL BITS MOVED BETWEEN THE 7600, CRAY AND TMS-4 (total of bits read and written)

Mass storage activity at NCAR expressed in bits moved per month and number of Volume Serial Numbers (VSN's) or data volumes, which are roughly equivalent to ordinary half-inch magnetic tapes.
<table>
<thead>
<tr>
<th>Data</th>
<th>Volume Through 1981 (Bits)</th>
<th>Added Each Year (Bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. All global, hemispheric and LFM analyses from NMC starting 1963</td>
<td>$1.49 \times 10^{11}$</td>
<td>$2.2 \times 10^{10}$</td>
</tr>
<tr>
<td>2. Surface and upper air observations from NMC starting 1963. Surface from 1976. Global</td>
<td>$9.9 \times 10^{10}$</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>3. All US raobs from 1948 from NCC, Asheville. Packed</td>
<td>$1.12 \times 10^{10}$</td>
<td>$3.68 \times 10^{8}$</td>
</tr>
<tr>
<td>4. FGGE year global analyses from ECMWF</td>
<td>$2.39 \times 10^{10}$</td>
<td>N/A</td>
</tr>
<tr>
<td>5. 107 million older surface synoptic observations from USAF (4900 station-decades)</td>
<td>$1.2 \times 10^{11}$</td>
<td>--</td>
</tr>
<tr>
<td>6. World ocean ship data from 1854-1980 (70 million observations)</td>
<td>$1.1 \times 10^{11}$</td>
<td>--</td>
</tr>
</tbody>
</table>
2. **Solar Orbiting Telescope**

This 1.25-meter orbiting telescope is planned for the 1985-86 period. It will take high resolution "pictures" of the sun each two seconds to give information about the sun's hydrodynamics and magnetic structure. Each picture in one wavelength is 1000 x 1000 pixels with about 10 bits per pixel, thus 10^7 bits of picture data plus housekeeping data each 2 seconds. Pictures are taken in 10 to 15 different wavelengths.

In the data processing steps, movies will be made to give added insight into what phenomena are happening and what calculations are needed. Two dimensional Fourier transforms are needed to obtain winds and scale sizes. Magnetic fields will also be calculated. Some of these processing steps involve a significant amount of computing per picture and there are many pictures.

Data will be obtained for one week each year, producing about 3 x 10^5 frames, or about 4 x 10^{12} bits with housekeeping information. Tasks for archiving, manipulation, and calculations with the data all require sizeable resources.

3. **Climate Models**

NCAR climate researchers maintain community climate models that are used in many joint research projects with university scientists. If computing capacity is available to accomplish planned research, the present use will grow by a factor of 4 to 8 to become as in the table below. About 20% of the computing time listed below is data processing. The data volume has been estimated by assuming that an archive is made each 12 hours of simulated time, that 100 to 120 parameter-levels are saved for each (9 layer run), 32 bits per number are used, and that a low resolution 40 x 40 grid (about 7.5 degrees) is used as planned. The Climate Section examined the possibility of using a much slower computer to handle the data processing. Since the equivalent of 500 CRAY scalar mode hours is 18,750 VAX hours (8000 hours in a full-time year), it doesn't appear possible or practical to unload this task onto a VAX class machine.

(Text continues on next page)
### Number of Equivalent CRAY-1A Hours Needed Each Year For Climate Models

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Number Simulated Days or Years</th>
<th>Comp Time (Hours) CRAY-1A</th>
<th>Archive Bits Times 10^11</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. CCM (15 wave, 9 level) Ocean temp given</td>
<td>7200</td>
<td>240</td>
<td>97</td>
</tr>
<tr>
<td>2. CCM (30 wave, 12 level) Ocean temp given</td>
<td>7200</td>
<td>1200</td>
<td>111</td>
</tr>
<tr>
<td>3. CCM (15 wave, 18 level) Stratospheric version</td>
<td>7200</td>
<td>432</td>
<td>177</td>
</tr>
<tr>
<td>4. CCM (15 wave, 9 level) Coupled to ocean-CO₂, trace gases</td>
<td>7200</td>
<td>360</td>
<td>97</td>
</tr>
<tr>
<td>5. Climate ocean models</td>
<td>100 years</td>
<td>500</td>
<td>130</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>2732</td>
<td>6.12 x 10^{11} bits each year</td>
</tr>
</tbody>
</table>

These estimates are included in the total estimate of resources required for climate research, or discussed previously in this chapter.

4. **Oceanographic Data from the Topex Satellite:**

Late in this decade, NASA plans to launch an oceanographic satellite able to measure winds and surface geostrophic currents over the world's oceans. Data from the satellite will be processed and archived by NASA, but the data will be of interest to oceanographers and meteorologists, particularly those interested in modelling the general circulation of the atmosphere, its response to winds, and its influence on the earth's climate. Much of this work could only be done on a large computer such as that at NCAR.

The volume of basic data is expected to be $10^{11}$ bits of data per year, for five years. The essential data will include maps of sea surface topography on a 250 km grid every 10 day, maps of wind speed on a 50 km grid every two days, and ancillary data on the satellite orbit and the oceanic geoid.

To use these data, two large problems must be solved. First, Wunsch and Gaposchkin (Reviews of Geophysics and Space Physics 18, 725-745) point out that the surface topography, geoid, and satellite orbit are all unknown, and that data from the satellite, observations of the satellite orbit, and geodetic information should all be inverted together to obtain the best estimates of these fields. Secondly, the calculated field of oceanic topography must be used with the best estimates of the internal density field of the ocean from classical hydrography to produce estimates of the general circulation of the
ocean. Both are very large inverse problems, both will require very large fast computers for solutions.

5. Radar Data

During the past year, NCAR radars were used to support 3 major experiments: CCPOE in Montana (1600 tapes at 1600 BPI and 400 at 6250 BPI), Seattle winter (1000 tapes at 1600 BPI) and Sierra (300 tapes). This is $1.25 \times 10^{12}$ bits per year. This rate will increase to $2.5 \times 3.5 \times 10^{12}$ bits per year in the 1986-87 time period, as other major storm-scale experiments are mounted and after a rapid scan radar becomes available in about 1986. From an experiment, 20 to 100% of the data is cataloged. About one percent must be fully analyzed.

The processing procedure for such data is to use a VAX to plot and edit the data, a task best done in interactive mode. Then tapes are mounted in off hours to move the data to the TBM mass store. About $2.5 \times 10^{11}$ bits of 1981 year's data has been moved to 6 mass storage reels of tape. When a case is analyzed, the points must undergo a massive coordinate transformation. This takes about 15 to 20 minutes of CDC 7600 time for each $8 \times 10^6$ bits of data. The same task takes 2.5 hours on the VAX. If $3 \times 10^{10}$ bits (1% of data) were processed each year, the transformation would take 113 hours of 7600 time or about 30 hours of CRAY-1 time.


The Coronagraph/Polarimeter, the HAO/NCAR telescope on board the NASA Solar Maximum Mission satellite, gathered an unprecedented high-quality data set during the lifetime of the mission. In the nine months of operation of the telescope, February 1980 to November 1980, some 30,000 digitized images of the solar corona were received at NASA Goddard Space Flight Center. These images were shipped to the NCAR Computing Facility and ultimately preprocessed and stored on the TBM. Each low resolution image contains some $1.6 \times 10^6$ data bits, while high-resolution images represent a factor of four increase in volume. Thus, the SMM data base consists of approximately $8 \times 10^{10}$ bits. The average data collection rate was 200-250 images per day.

About 90% of the images were preprocessed and a working copy of each image was generated on the DICOMED. During the 9-month operation period, this processing of incoming data required about 20 CCU of CRAY time per month and 23,000 CRU's of 7600 time per month.

In HAO's current phase of the data analysis, without any additional data coming in, three to five CCU's per month are used. A significant portion of this usage has, in the recent past, been used in calibrating the data. To calibrate one volume of data consisting of about 50 C/P images, .2 CCU is required.

The SMM satellite and the HAO/NCAR telescope are to be repaired in April 1984 by the Space Shuttle. At that time, operations will again commence. Data will then be accumulated at essentially the same rate as the first phase of the mission.
7. Meteorological Satellite Data

Many satellite data sets are high in volume; NCAR has thus far used very little of these data. The NOAA Tiros-N satellite series produces 812 gigabits of 4 Km resolution global data and 192 gigabits of sounder data each year, thus about $10^{12}$ bits per year.

The two geostationary GOES satellites dominate the data volume from meteorological satellites. They take pictures of 1/4 of the earth each half hour at a resolution of 1 Km visible and 8 Km IR. The volume from each satellite is $2.55 \times 10^{12}$ bits each year. The University of Wisconsin probably has the world's largest data archive. They have been saving all of this data on Sony tape-recorders from 1978. The recorders have high error rates, but that is okay for these data. They use small computers to manipulate portions of the data. The problem is that larger amounts of these data need to be processed to derive cloud and other information. An International Satellite Cloud Climatology Project has been started to define data subsets, and to do large amounts of processing on five years of future data.

Conclusion

It has widely been recognized that data processing in atmospheric research will be one of the major challenges of the 1980s. A spectrum of computing capabilities are required to meet this challenge. Much can be done by individual scientific groups on VAX-class machines. However, the largest tasks, such as are discussed in this section, will be done most efficiently and effectively on a Class VI or VAC machine.

Data processing requirements have significant implications for channel bandwidth and archiving requirements. NCAR's plans for the overall enhancement of its computing capability, as discussed in Chapter IV, show the AVC embedded in an overall system that takes these requirements into account.
Chapter III
SURVEY OF COMMUNITY OPINION

This chapter discusses responses to a letter-questionnaire asking the views of the scientific community about the value of an AVC to the advancement of the science. The letter (Appendix E) was sent to a total of 850 persons in the following groups:

1. All principal investigators currently using the Scientific Computing Division facilities for their research programs

2. All principal investigators who had used the SCD facilities in the past but no longer had active projects on our computers

3. All faculty members, regardless of whether they had used the SCD facilities, in all graduate departments of atmospheric sciences, oceanography, and solar physics, and departments of other disciplines in which it was known that work related to the atmospheric sciences was being done, as listed in the American Meteorological Society publication, Curricula in the Atmospheric and Ocean Sciences, 1980

4. All Members' Representatives of UCAR universities

5. All members of the NCAR scientific staff.

As of 8 September 1982, the views of 227 members of the scientific community had been received in 149 responses. (Twenty-five letters represented the views of more than one scientist.) The views of 32 NCAR scientific staff members were also received.

A list of institutions from which responses were received is given in Appendix F.

The responses to the letter-questionnaire supplied information on two principal questions:

1. What are the major scientific developments in the atmospheric and related sciences that can be directly ascribed to access to the CRAY-1A at NCAR since 1977?

2. What major atmospheric research efforts of the 1980s will require either (a) the resources of an AVC or (b) such a large amount of Class VI resources that it is unlikely to be available unless the overall resource in the community is greatly increased.

The letter-questionnaire also asked for opinions on demands for computer resources related to data processing activities in the next several years.
Analysis of Responses

As discussed below, the preponderance of responses indicated the great value of the CRAY-IA computer, with its supporting mass storage, graphics, and communications systems, in attacking a broad spectrum of diverse problems, and they indicated that the same broad range of problems now requires even greater computer resources.

In the following sections, we first discuss the use of the CRAY-IA since 1977, quoting from many responses received, and then discuss the respondents' views on problems requiring either an AVC or greatly increased amounts of Class VI resources. In this chapter, some 60 of the 149 responses received are cited.

Finally, the negative responses are discussed.

A selection of letters from leaders of the community supporting NCAR acquisition of the AVC is contained in Appendix G.

Science Supported by the NCAR CRAY-IA, 1977-1982

Responses to the letter-questionnaire show a broad consensus that availability of the CRAY-IA was an essential factor in many of the most important scientific advances in the past several years.

Two major activities are constantly referred to in the responses: modeling and data analysis. These two major activities are, of course, synergistic. The field data provide new insight into phenomena so that model simulations can be improved, while the models help to focus experiments on crucial questions and can in turn be verified by the field data.

Many respondents reflect satisfaction with the research that has begun using the CRAY-IA, and discuss a broad range of topics where important advances have been produced. The accessibility of the NCAR facility is often emphasized:

• "It is evident that the expansion of NCAR computing power into the CRAY-IA class has opened many avenues of promising new research. Whereas the early utilization of high speed computers was mainly in the numerical weather prediction problem, as evidenced by the successes of such groups as the Geophysical Fluid Dynamics Laboratory and the National Meteorological Center, the NCAR facility opened the way to large computing in many areas, including small scale processes such as clouds, statistical turbulence, detailed boundary layers, line-scale models, and a host of problems with which I am not closely related. It would be arrogant to point to any one of these uses as 'most important'; however, the overall impact of applying computing capability to so many pertinent issues at the same time is remarkable and truly noteworthy. I would not anticipate that the expansion will abate and added computing strength will continue the strong growth of research in the atmospheric sciences." (University of Maryland)*

* Respondents' institutions are cited throughout this chapter.
"The nature of our research, of course, biases our response. We feel that improvement in the understanding of numerical simulation or turbulence and atmospheric turbulence has been a major consequence of the availability of the CRAY-1A. However, many other important atmospheric studies have made use of the CRAY-1A, particularly oceanographic modeling, mesoscale studies, and general circulation studies. The CRAY-1A has been a first step towards providing numerical modeling capability which would allow detailed evaluation of atmospheric models and their comparison against actual observation." (Rutgers University)

"I would estimate that eighty percent of the global scale, cloud scale, and mesoscale modeling done on the CRAY-1A (including my own) could not have been done on a lesser machine. Of course, research advances arise from thought and not from the mindless 'number crunching' of computers. But almost every major advance in the above areas of modeling came about because researchers had the tool to test conceptual advances. The CRAY-1A quite simply has been the sine qua non of modeling research." (State University of New York at Albany)

The CRAY has provided "added resolution, both spatial and temporal, to flow simulations. The computer is rapidly becoming a viable contender for the role of decision-maker when thorny questions about our understanding of properties of turbulent flows must be decided. Although experiment will probably always be the only true standard, numerical experiments, skillfully performed and carefully interpreted, frequently can evaluate quantities that are extremely cumbersome to measure. Thus, issues on which experiments may provide hardly a clue can be addressed. In atmospheric science the ability to experiment on a computer with a model global circulation is extremely valuable. The equations are so complex that only rather crude predictions of a general nature can result from theory. The computer allows us to explore the tremendous space of solutions of these equations. The bigger and faster the computer, the more wide-ranging and probing the exploration." (Brown University)

"First, the most important result arising from use of the CRAY-1A has been the ability of the entire atmospheric sciences community to obtain state-of-the-art computing power. The scale of operations allowable on smaller machines was not sufficient to provide researchers with routine access to very high speed computing. Second, the CRAY-1A has turned large experimental models into practical research tools. For example, the entire research community now has access to a general circulation model, the community climate model. In the pre-CRAY era, when only a handful of general circulation model runs could be done in a year, this would have been impossible." (Advanced Study Program/NCAR)

"The CRAY-1A has greatly enhanced modeling efforts. This includes cloud models, atmospheric and oceanic general circulation models (GCM). Not only does the CRAY-1A allow one to make these models more accurate, but it also gives more people the necessary tool to attack these problems. This, of course, makes for more rapid progress in our science." (Colorado State University)
Other scientists emphasize GCM research in boundary layer turbulence, climate, air-sea interactions, air quality, and tropospheric studies. The variety of the experiments is impressive as is the progress of the research in the last five years.

A large number of respondents comment on progress in specific areas. The following are excerpts from some of the more extensive responses:

Mesoscale

- "The most important results arising from the use of the CRAY-1A are the additional details which have been achieved in modeling results, particularly in three-dimensional mesoscale models. Such results have allowed a better understanding of the physics governing the specifically scaled processes and the scale interactions taking place between the various scales." (South Dakota School of Mines and Technology)

- "With the availability of advanced computers such as the CRAY-1A, three-dimensional cloud or storm models have become the standard for models of convective clouds and storms. The models have furthered our understanding of the processes contributing to the formation of mesocyclones, and propagation of convective storms, particularly factors contributing to storm splitting, the role of mesoscale convergence in regulating convective cloud intensity and rainfall, and examination of the modification potential of convective clouds. Fine-mesh, three-dimensional models of stratocumulus have generated data which has been statistically analyzed and interpreted to enable the formulation of one-dimensional predictive models of these cloud systems. Moreover, because of their 'realistic' replication of certain observed features of convective clouds, three-dimensional models have become a powerful tool in the analysis and interpretation of observed cloud phenomena. Thus in the last five years we have seen the parallel rise of major observing systems of convective storms, including multiple-Doppler radar, telemetered mesonet stations, sophisticated airborne observation platforms, and three-dimensional cloud models. The 'perspective' provided by these cloud models has had a major impact upon the interpretation and synthesis of the vast quantities of data that are produced by these observing systems." (Colorado State University)

Weather Prediction

- "The most important result arising from the use of the NCAR CRAY-1A has been the advancement of our understanding of the initialization problem for short-range forecasting through the normal mode work carried out by many people." (Atmospheric Analysis and Prediction Division (AAP)/NCAR)

- "The skill of short-to medium-range (up to five days or so) predictions of large-scale mid tropospheric flow patterns produced by the European Centre for Medium Range Weather Forecasts and the National Meteorological Center global models has recently improved significantly. This improvement results from the use of more accurate numerical approximations to formulate prediction models (higher vertical and horizontal
resolutions and the use of the global domain for modeling and analysis) and extensive meteorological observations (from satellites, aircraft, ships, and ocean buoys, in addition to conventional surface and upper-air stations) as inputs to the prediction models. It is clear that without having high speed computers of the CRAY-1A class, we were unable to meet the demand of computer capability for advanced data processing and fast time integration of numerical models." (AAP/NCAR)

Climate

- "The development of the NCAR community climate model was greatly facilitated by the presence of a machine such as the CRAY-1A. The numerous runs which have been made with the model would not have been a very practical undertaking with an earlier-generation machine. The computing power which was available to us permitted extensive testing of the model, and this is a vital part in putting together a model in which one has some confidence. In isolating those aspects of the radiation code, for example, which gave rise to the substantially improved zonal-wind simulations, a countless number of runs had to be made with the model. The thoroughness of that study, as well as its timely completion, owe in large measure to the existence of the CRAY-1A." (University of Miami)

Oceanography

- "The great advances on the CRAY-1A have been the development of eddy-resolving general circulation models and geostrophic turbulence models. Eddy resolving ocean circulation experiments have also been important. A series of dynamical studies has been carried out primarily of the ocean eddy field with particular emphasis on several potentially operative eddy generation processes; the accompanying eddy-mean field interactions; and the eddy-induced ocean transports of momentum, heat and dissolved tracers." (Woods Hole Oceanographic Institution)

- "Important physical oceanographic research has been the studies of geostrophic turbulence (strongly interacting, quasi-geostrophic flow). Only numerical calculations can be used to investigate such flows." (Texas A&M University)

Chemistry

- "The CRAY-1A computer has also been necessary for the development of comprehensive models of auroral and chemical-dynamic transport processes. These large numerical models give insight into nonlinear coupled physical and chemical processes. These models are two-dimensional and they are being used to examine the role of major and minor neutral constituents such as O, O₂, N₂, N₂(D), NO and N₂(S) on the chemical balance of the upper atmosphere and their feedback on dynamic processes. Our calculations indicate that the thermospheric sources of NO are important for stratospheric chemistry and also that the radiative cooling by 5.3μm emissions of NO is important for the dynamic structure of the upper atmosphere. During the next decade these models will be expanded to three-dimensions and eventually coupled to the dynamics of the tropospheric general circulation model, thus requiring at least a doubling or tripling
of our computer resources currently devoted to this project." (Atmospheric Chemistry and Aeronomy Division (ACAD)/NCAR)

- Those who have begun the coupling of meteorology and chemistry and surface ocean processes represent important beginnings in coupling... upper atmospheric chemistry and dynamics. In my own area, it has been very enlightening to be able to construct and run large models with complex and interactive chemical processes." (ACAD/NCAR)

Upper Atmosphere

- "Large scale models of atmospheric circulation, both tropospheric and above, would have not developed without the CRAY-1A. Without these, our large acquisition of atmospheric data would have rapidly become useless and progress would be very slow in atmospheric research." (Utah State University)

- "The most important results that have been obtained from the use of the NCAR CRAY-1A computer are in obtaining a scientific understanding of various nonlinear dynamic, chemical, physical, and electrical coupling processes that occur naturally in the earth's atmosphere and in response to auroral activity. This insight is in part derived from numerical experiments and in part from comparing predictions with ground-based and satellite data. I believe that by constructing a comprehensive coupled model of dynamic, chemical and electrical processes we may make some progress toward understanding the basic processes operating in the upper atmosphere and also in understanding the effects of solar variability and perturbations on the earth's atmosphere." (ACAD/NCAR)

Solar and Astrophysical Research

- "In my opinion, the major theoretical advances that have been made possible by the CRAY-1A computer are those involving the development of detailed models based on physical mechanisms for producing stellar winds in hot stars, and the parallel development of radiative transfer techniques that can predict the spectra resultant from such spherically symmetric outflows. The former include the continuing refinement of the radiative-driven wind theory originally proposed by Castor, Abbott, and Klein (1975, Astrophys.J. 195, 157) while the latter include the major series in the Astrophysical Journal from 1976 to 1980 by Mihalas, Kunasz, and others on the transfer of radiation in a moving atmosphere using the Co-Moving Frame Approach." (University of Colorado)

- "I feel that the radiative transfer techniques that have been developed and applied to numerous problems over the years both by in-house NCAR High Altitude Observatory staff, and by outsiders, have been the most important contribution arising from the use of the NCAR computing facility. The problems range from the winds of hot stars, to the accretion disks surrounding compact X-ray sources, to chromospheric emission spectra of late-type stars, to detailed studies of solar convection and oscillations, just to name a few examples." (University of Colorado)
The first fully nonlinear hydromagnetic dynamo driven by convection in a rotating spherical shell, developed at NCAR, is allowing the study of dynamo processes relevant to the solar cycle problem at a unique level of physical realism, though still quite simple compared to the sun. The detailed interaction between the dynamics maintaining the differential rotation and the induction processes responsible for the magnetic fields can be unraveled. (High Altitude Observatory/NCAR)

Turbulence

In our judgment, the most important results arising from use of the NCAR CRAY-I A computer have been fundamental advances in the theory of fluid turbulence. Among these have been the development and implementation of the ideas of Kraichnan and others, concerning Lyapunov stability (exponential separation of phase space elements), with its serious implications for weather prediction, and the studies of solitary wave and other structures, with relevance to blocking fronts and intermittency. Very recent work on the CRAY-I A by Frisch, Örszeg, and others promises to offer new paradigms for thinking about turbulence, such as the notion of Poincare maps in real space in analyzing vorticity and its relevance to the onset of turbulence. Such problems, in our estimation, will continue to be the most important the science will be addressing between now and 1990. All of these efforts stretch the capabilities of the existing facility and even projected augmentations. Even with a ten-fold increase in central memory, progress in the fundamental theory of fluid and plasma turbulence will be computer-limited. (University of Colorado)

Fully-developed Langmuir wave turbulence in the solar wind has been studied and characterized in great depth, taking into account the major physical effects of wave-wave interaction and self-focusing. Research will continue to address problems of plasma turbulence, with emphasis on the interaction between high and low frequency turbulence, onset conditions, and fundamental research on fluid turbulence being carried out at NCAR (Leith, Herring) and elsewhere. The physical relevance of the research will encompass solar physics, solar wind physics, ionospheric physics, and beam-plasma interaction. (University of Colorado)

Projects Requiring the AVC

Responses to the letter-questionnaire show wide community support for the procurement of the AVC, based on three general considerations:

- The AVC will allow modelers in all atmospheric disciplines to enhance the realism of their models. Many physical and chemical phenomena, previously parameterized or ignored, can be directly included in models running on the AVC. Crucial here are both of the major hardware characteristics of the AVC—much enlarged directly addressable memory and a much faster central processing unit (CPU) compared with Class VI machines.

- Intense awareness and concern was expressed about the magnitude of the data-handling problems of the next decade. Introduction of new communications networks and procurement of a new mass storage
device both planned for NCAR in coming years, will help allay concerns in these areas. Still, there remains a grave concern as to the availability of adequate CPU power at NCAR to meet the needs of the community.

Although the letter-questionnaire did not specifically ask for opinions about current adequacy of available computer resources at NCAR, some 32 respondents volunteered that they cannot obtain large enough allocations of CRAY-1A time to carry out computer-intensive work in an effective manner, and/or that the current saturation of the NCAR facility was a seriously inhibiting factor in doing effective and timely work. The power of the AVC would expedite much science now being slowed or not undertaken because of a lack of Class VI computing capacity.

The following table shows the number of respondent letters that mentioned various areas of research as requiring either AVC or sizeable increases in Class VI-computer resources to make significant progress in the 1980s:

TABLE 8

<table>
<thead>
<tr>
<th>Number of Responses Stating AVC Needs in Various Subdisciplines</th>
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<tbody>
<tr>
<td>(Total Responses = 149)</td>
</tr>
<tr>
<td>Cloud Models</td>
</tr>
<tr>
<td>Mesoscale Studies</td>
</tr>
<tr>
<td>Cyclone and Larger-Scale Studies</td>
</tr>
<tr>
<td>Climate Modeling and Related Work</td>
</tr>
<tr>
<td>Solar and Interplanetary Physics</td>
</tr>
<tr>
<td>Chemistry</td>
</tr>
<tr>
<td>Oceanography</td>
</tr>
<tr>
<td>Turbulence Theory</td>
</tr>
</tbody>
</table>

NOTE: Some responses cited more than one area as requiring the resources of the AVC in the 1980s.

Research Requiring Greatly Increased Computer Power in the 1980s

In the next sections, excerpts from respondents' descriptions of modeling projects for the 1980s will be given, followed by a brief summary of many respondents' statements of greatly increased computing needs related to data processing and analysis.

1. Modeling
   a. Clouds

   In the detailed modeling of clouds, explicit inclusion of cloud physics would be possible only with the AVC (St. Louis University), for example, the mechanisms of thunderstorm electrification (University of Hawaii at Manoa). Important refinements would include elimination of the axisymmetric limitation on tornado models (Purdue...
University) and inclusion of aqueous chemistry (South Dakota School of Mines and Technology).

b. Atmospheric Circulations

There are enormous opportunities in every aspect of mesoscale modeling. (University of Wisconsin at Madison), for example, modeling the details of severe convective storms including fine details of convection (Massachusetts Institute of Technology and University of California at San Diego). Another area of profound importance is the coupling of synoptic scale and mesoscale models to gain a better understanding of heavy precipitation-producing weather systems (University of Wisconsin at Milwaukee). In weather forecasting, there will be many opportunities, such as accurate forecasting of severe local storms three to 24 hours in advance (University of Wisconsin at Madison).

There has been a growing recognition of the importance of tropical weather conditions on the behavior of the atmosphere in temperate latitudes. The AVC will provide a number of opportunities for clarifying this relationship. The new computer will permit initial development of explicit models of tropical circulation combining both cyclone scale (200 km) and cumulus scale (2 km) phenomena (Colorado State University). One respondent expressed his conviction that the AVC would make possible a major thrust in low latitude predictability problems, and that the AVC would enormously facilitate the refinement of initialization procedures and the treatment of physics in midrange weather prediction models, especially at tropical latitudes (Florida State University). The AVC will spur development of models that will lead to an understanding of tropical and extratropical cyclogenesis, together with better understanding and prediction of mesoscale convective weather systems (Pennsylvania State University).

Several respondents emphasized the improvement of numerical weather prediction techniques, including improved mesoscale forecast capability and improved long term forecast capability (University of Chicago), as well as consistent accuracy in five-day weather forecasts, and accurate forecasting of severe local storms three to 24 hours in advance (University of Wisconsin at Madison). Improved regional and mesoscale weather prediction is also expected (Drexel University).

c. Climate

There are similarly extensive opportunities for climate modeling of several kinds, according to many respondents. Such models would lead to numerous advances, such as an improved theory of the climate system including: chemistry, with application to problems such as the CO₂ problem (University of Wisconsin at Madison); the merging of dynamics and chemistry in a comprehensive climate model (Harvard); the merging of atmospheric chemistry and radiation effects explicitly in climate models (University of Oklahoma); and
coupled models in general (University of Colorado), for example, the coupling of climate and ice-sheet models for Ice Age simulation (NCAR).

The AVC would also make feasible the treatment of interannual climatic variability and climate change (University of Washington), and studies of short-term climate variations (Oregon State University).

In large-scale dynamics, several respondents intend to study mechanisms of atmospheric blocking and interannual climate variability (University of California at Davis). The power of the AVC is essential to progress in understanding the behavior of long waves in the atmosphere and in developing prediction models (NCAR).

With respect to boundary-layer problems, the AVC should provide improved treatment of ocean-atmosphere coupling in climate and other models (University of California at Davis), of modeling the effect of sea-surface temperature anomalies on the general circulation of the atmosphere (University of Miami), and of refining rough-terrain boundary-layer effects in general circulation models (University of Utah).

d. Solar Physics

There were a number of problems on solar structure and radiation to be treated with the AVC. These include:

- Modeling of solar and magnetospheric phenomena with highly nonlinear plasma dynamics (Pennsylvania State University), and plasma turbulence (University of Colorado).
- Multidimensional radiative transfer computations (University of Colorado), including hydrodynamics (Cornell University).
- Multidimensional treatments of the small-scale structure of the solar atmosphere; increasingly nonclassical treatments of the microscopic physics of the solar atmosphere; the structure, dynamics, and magnetohydrodynamics of the solar interior; and acceleration of highly energetic particles in the solar atmosphere (University of California at San Diego).
- A systematic study of nonlinear hydromagnetic dynamos driven by compressibility on convection in a rotating circular shell (i.e., the sun), and improvement in understanding, in both qualitative and quantitative terms, the nature and cause of solar activity cycles (NCAR).

Among problems in interplanetary and magnetospheric studies, respondents intend to develop a three-dimensional time-dependent magnetohydrodynamic simulation model of solar interplanetary dynamics, which may lead to understanding the fundamental mechanisms of
solar-terrestrial relations (University of Alabama at Huntsville); to carry out self-consistent simulations of auroral arc formation, with magnetosphere-ionosphere coupling (a problem requiring a minimum of 10 million words of available central memory) (University of Alaska); to conduct two- and three-dimensional modeling of the magnetosphere; and to study high-altitude motion problems and infrared radiation transport in the earth's atmosphere (Purdue University).

e. Atmospheric Chemistry

In atmospheric chemistry, respondents intend to use the AVC in studies of global atmospheric chemical cycles (University of Washington); general studies involving modeling of chemistry and transport in planetary atmospheres (University of Michigan); stratospheric and tropospheric ozone, H\textsuperscript{+} concentrations in aerosols and rains (acid rain), and toxic substances in the atmosphere (New York University); incorporation of aqueous chemistry into cloud models (South Dakota School of Mines and Technology); merging of chemistry and dynamics in comprehensive models (Harvard); "ab initio" computation of energy levels of high stratospheric atomic and molecular species (University of Denver); and dynamics of the collision of electrons with atoms and molecules (California Institute of Technology).

f. Oceanographic Circulation

Among the oceanographic problems respondents intend to run on an AVC are:

Development of improved eddy-resolving ocean models (Woods Hole Oceanographic Institution, Oregon State University, NCAR); determination of Lagrangian trajectories and dynamic balances following floats in oceanic general circulation models (Woods Hole Oceanographic Institution); interactive ocean-atmosphere models for studying climate feedback mechanisms (University of Miami, Texas A&M University); tropical ocean models on the interannual time scale and ice-ocean-air interaction models (Florida State University); the interaction among the Great Lakes, the atmosphere, and regional weather (University of Miami). A respondent from Texas A&M University states: "In my judgment, the most important problem to be addressed by physical oceanographers is that of describing, and building the capability to monitor, the general circulation of the world ocean. It is intellectually stimulating, and it is of importance to studies of both climate and dispersal of man-made and natural materials introduced into the ocean."

g. Turbulence

Respondents mentioned several problems in turbulence theory requiring the speed and memory of an AVC. These included: turbulent flows at high Reynolds number (Massachusetts Institute of Technology); numerical models which incorporate realistic physics and which
better resolve the turbulent spectrum (Sacramento Peak Observatory); coherent jetlike or vortexlike flows of relevance to atmospheric and oceanic phenomena, and three-dimensional modeling of turbulence (University of Pittsburgh); three-dimensional interactions of vortex filaments and vortex rings (University of Utah).

2. Data Handling

In the next decade, the volume of data of atmospheric, oceanographic, and solar interest is likely to reach almost overwhelming proportions. Some 62 respondents mentioned the need for increased data-handling capability. New satellites will be transmitting data at rates approaching $10^{11}$ bits per second per satellite. Though NCAR will not be responsible for the reduction of raw satellite data, it is estimated that the flow of satellite data of interest to users of the NCAR computers will be on the order of $10^{10}$ bits per year. These data will be manipulated and customized by the Data Support Group of the NCAR Scientific Computing Division into forms useful for research purposes.

The development of new aircraft instrumentation for atmospheric chemistry and cloud physics implies data flows of large magnitude that will have to be managed here at NCAR (University of Wisconsin at Madison).

The development of rapid-scan doppler radars will demand a very high mass storage volume for archiving purposes, in order that subsequent model experiments will have access to them.

Negative Responses

Of the 226 persons represented by the responses, seven individual responses have been classified as "negative."

A respondent from the Desert Research Institute of the University of Nevada expressed a wish that NCAR commit funding to making computing facilities easier to use, and therefore more productive of the scientists' time, rather than simply adding another bigger computing engine.

A scientist at NASA's/Goddard Laboratory for Atmospheric Studies (GLAS) held that adequate Class VI capacity was available for university users when the resources of NCAR, GLAS, and the Geophysical Fluid Dynamics Laboratory were taken together. That respondent also suggested that NCAR invest in a number of sophisticated interactive graphics facilities, geographically dispersed, and develop NCAR's mass storage capability.

A respondent from Florida State University has suggested that the money used to procure the advanced machine might be better spent procuring a number of CDC CYBER 760 computers to be installed at UCAR universities. (The CYBER 760 is a machine with less capacity to handle large computations than the CRAY-1A, and is of somewhat older architecture.)

The remaining "negative" letters raise questions such as the ease of use, the assertion that funds should be spent on improved measuring techniques rather than enhanced computational facilities, and stability of operating
systems.

UCAR believes that the current long-range plan for the NCAR Scientific Computing Division (see Chapter IV) is responsive to the concerns about accessibility, ease of use (particularly interactive graphics), and the stability of NCAR's operating systems.

UCAR disagrees with the assertion that existing Class VI computers at NCAR and at various government atmospheric research laboratories can meet the demand for Class VI-or-better computers by the university community. There is striking agreement among the total estimates given in Chapter II, the responses to the letter-questionnaire, and the 1981 NCAR Computer Users' Conference that the equivalent of at least five CRAY-1As are now required for adequate progress in highest-priority research across the atmospheric sciences. Moreover, and perhaps more important, dispersed Class VI capabilities can in no way serve the throughput or memory requirements for coupled ocean-atmosphere models, storm modeling, solar modeling, and fundamental turbulence studies. Only an AVC will be adequate for these studies.

Moreover, it is not clear that Class VI facilities at other locations will be as openly accessible as NCAR's capabilities are.

The cost and effectiveness advantages of an AVC computer at NCAR, as compared to using dispersed Class VI capabilities, are discussed more fully in Chapter I.