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JUSTIFICATION DOCUMENT

FOR THE

UPGRADE OF THE

CRAY X-MP/48 SUPERCOMPUTER

Note: NCAR got the Cray Y-MP/8-64.
It arrived May 21, 1990
-Roy Jaffe

National Center for Atmospheric Research
Boulder, Colorado
September 1, 1989

From John Sloan
Mar 1996
He was head
of high end
systems
-Roy Jaffe
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ACRONYMS

A list of acronyms used throughout this document appears in Appendix A.
EXECUTIVE SUMMARY

Almost all of the priority research areas in atmospheric and ocean sciences (climate and ocean dynamics, atmospheric chemistry, mesoscale meteorology, and solar physics) make extensive use of simulation models that require supercomputers. Further, the set of tractable simulations is limited by the capability of available computing equipment. Put another way, a more powerful supercomputer expands the set of tractable simulations thus yielding new scientific understanding and insights.

By the early 1990s, the next generation of supercomputers will be available and will offer an order of magnitude increase in power relative to what is now state-of-the-art equipment. With this equipment, the atmospheric and ocean sciences will have a truly significant increase in computing capability and capacity permitting rapid scientific progress through high-resolution simulations, coupled models, improved parameterizations and large databases.

This report documents a suite of problems in each of the subdisciplines of atmospheric and oceanic science that can be addressed with the next generation of supercomputers, but cannot be reasonably addressed with existing equipment. Broadly, a next generation supercomputer will make possible coupled models, higher resolution simulations and more accurate parameterizations. Thus, this document provides both the scientific justification and the resulting technical implications for the enhancement of the supercomputing environment at the National Center for Atmospheric Research. Moreover, this upgrade supports the following missions of NCAR which has been defined by the UCAR Board of Trustees and endorsed by the National Science Foundation:

"In cooperation with university research groups and other organizations, to identify, develop, and make accessible selected major research services and facilities of outstanding quality required by the universities and NCAR for effective progress in atmospheric research"
programs. NCAR will be responsible to assure the most effective use of these facilities and services by scientists in the universities and NCAR."

"In cooperation with universities and other organizations, to plan and carry out research programs of highest quality on selected scientific problems of great national and international importance and scope. . . . It is appropriate that most of the research at NCAR be on problems that are characterized by their central importance to society, scientific interest, and by the requirement for large-scale, coordinated thrusts by teams of scientists from a number of institutions" [1].
1. INTRODUCTION

Historically, the atmospheric sciences have made extensive use of high-performance computers for modeling of weather, climate, oceans and related phenomena. For example, Version CCM1 of the NCAR Community Climate Model (CCM) is a three-dimensional (3-D) simulation that carries about 25 variables at each mesh point. Although the model averages over 80 million floating point operations per second (Mflops), following are memory and CPU requirements as a function of grid resolution:

<table>
<thead>
<tr>
<th>Grid Resolution</th>
<th>Points/Grid</th>
<th>Memory in Millions of Words</th>
<th>X-MP CPU Hours/10 years Simulated</th>
<th>Archive Gbits/CPU Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>R15</td>
<td>40 x 48</td>
<td>.51 Mwds</td>
<td>41.5</td>
<td>2.04</td>
</tr>
<tr>
<td>T31</td>
<td>48 x 96</td>
<td>.67 Mwds</td>
<td>121.6</td>
<td>1.51</td>
</tr>
<tr>
<td>T42</td>
<td>64 x 128</td>
<td>.82 Mwds</td>
<td>268.6</td>
<td>1.17</td>
</tr>
<tr>
<td>T63</td>
<td>96 x 192</td>
<td>1.2 Mwds</td>
<td>912.0</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 1. CCM1 without diurnal solar cycle

Clearly, use of CCM1 to carry out high resolution-decadal simulations, requires the most powerful computer available.

1.1 A More Powerful Computer Yields New Scientific Capability

The capability of a model is often paced, or limited, by the power of the computer that is available to execute it. That is, a more powerful computer makes possible more realistic models.
example, 15 years ago the Control Data 7600 was used for climate simulation and ten minutes of CPU time was required per 24 hours of simulated time. Because of limited computing time, models were typically formulated in the perpetual-January mode (i.e., with constant astronomical, chemical, and ocean forcing appropriate for the month of January) and at most, a few months, such as January and July, were simulated. Each month had to be run for several years to develop an adequate climatology. With the availability of the CRAY-1A and its high performance in vector mode, less than two minutes of CPU time were required per 24 hours of simulated time. This permitted climate researchers to venture beyond the perpetual-January mode and investigate such areas as the interannual variability of time-averaged atmospheric states.

Availability at NCAR of the CRAY X-MP/48 with a 256-million word SSD has likewise extended the scientific capability of models. For example:

- In mesoscale meteorology

  Major advances in the fundamental physics of the atmosphere's flow response to topography has been made on the CRAY X-MP/48 through the simulation of:

  - Up-slope snowstorms and orographic snow storms
  - Influence of terrain on typhoon dynamics
  - Thermally-forced flows and the role of thermally-forced circulations on the genesis of inertially stable mesoscale vorticities over the Rocky Mountains.
  - Hawaiian rainbands and Denver convergence zones.

The response to stratified flow over topography is an important input required in global climate models to improve weather predictions.
NCAR scientists successfully coupled a global version of the Community Climate Model to a global ocean model on the NCAR CRAY X-MP. After 30 years of simulation, results indicate a globally averaged surface air temperature increase of 1.6°C for instantaneously doubled carbon dioxide, whereas, for a 1% increase of carbon dioxide per year the temperature increased by 0.7°C. The simulation in the tropical Pacific showed, for the first time, warm and cold events similar to those found in the observed El Niño and La Niña sequence.

Scientists at the Naval Postgraduate School (Monterey, CA) and NCAR have developed a global ocean calculation model that is marginally able to resolve eddies. The model also reproduces known phenomena such as the Antarctic Circumpolar Current. This model requires over 1000 CPU hours per simulation on the X-MP and demonstrates the feasibility of high-resolution coupled ocean-atmospheric models using the next generation of supercomputers.

Models have been developed to help obtain an overall understanding of the basic structure of this region of the atmosphere and its response to solar and auroral variability. For example, the Thermospheric General Circulation Model (TGCM) is an integral part of the NSF Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) programs and figures in other NSAS and international programs. It is being used by nearly 100 university scientists, students, government and foreign colleagues for studies of thermosphere dynamics.
The point of these examples is that a more powerful computer expands the set of tractable simulations and thus yields new scientific capability. This is the primary reason for seeking a next generation supercomputer at NCAR. As summarized by the SCD Advisory Panel in their spring 1989 meeting:

All of NCAR's priority research areas (climate and ocean dynamics, atmospheric chemistry, mesoscale meteorology, and solar physics) require the extensive resource that the NCAR Scientific Computing Division provides. A similar statement can be made in regard to the many university-based atmospheric science investigations and to the collaborative efforts involving NCAR and university scientists.

By the very early 1990s, a ten-fold improvement in available computing power will make possible very significant advances in scientific knowledge regarding global change, ozone depletion, severe storms, and solar variability. This new computing power will make possible the use of high-resolution models and large databases which are genuinely adequate for their intended applications rather than merely marginal in scope.

1.2 Future Requirements

Section 2 of this document, "Future Scientific Requirements," was developed by members of the atmospheric and oceanographic sciences community who have specified the performance and increased memory requirements of more than 40 projects currently underway and to be undertaken by this community. These proposed projects involve the research efforts not only of many NCAR scientists, but also their university collaborators (see Attachment B), and many other university scientists. Many of these projects support major national undertakings such as climate and global change, etc. Individually, these projects require a supercomputer with 10 to 400 million words of memory. In aggregate, these important projects will need in excess of
1,000,000 single processor X-MP equivalent hours per year. Such projects are beyond the capability of the NCAR CRAY X-MP/48. Next generation supercomputers will provide an order of magnitude increase in processing speed and memory capacity, thus these projects can be addressed with them. To emphasize that a more powerful computer produces new science, throughout this document we discuss recent results from jobs run on the NCAR CRAY X-MP/48 that could not have been obtained with the CRAY-1A.

<table>
<thead>
<tr>
<th>Mesoscale</th>
<th>247,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>334,000</td>
</tr>
<tr>
<td>Chemistry</td>
<td>55,000</td>
</tr>
<tr>
<td>Ocean</td>
<td>335,000</td>
</tr>
<tr>
<td>Turbulence</td>
<td>66,000</td>
</tr>
<tr>
<td>Astrophysics</td>
<td>27,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1,064,000 X-MP CPU Hours/Year</td>
</tr>
</tbody>
</table>

= About 40 X-MP/48s
= About 15 Y-MP/8s
= About 5 CRAY3s

(Annual X-MP equivalent CPU hours)

Figure 2. Summary requirements for next generation supercomputer

1.3 The NCAR Scientific Computing Division

Since access to supercomputers and data is fundamental to research in the geosciences, the principal mission of NCAR’s SCD is to provide this community with:

- Supercomputing resources for the development and execution of large numerical simulations and for archiving and manipulation of large datasets

- Network and data communications capabilities required for a national user community to access NCAR computational and data resources.
A computing environment that emphasizes reliability, high performance, graphical display and user productivity.

Thus, NCAR’s SCD is a discipline-specific supercomputer facility. The overall environment is tailored for the atmospheric and ocean sciences. These disciplines have special needs in data archiving and handling because the simulations performed for the atmospheric and ocean sciences are anomalies in the larger world of scientific supercomputing activities. A major effort in several SCD sections is devoted to providing technological solutions for data archiving and handling problems and to assisting users with data problems. Special software in graphics, visualization, mathematics and data analysis also assists researchers in these disciplines.

Success in utilizing the capability of the next generation of supercomputers will require a transition to parallel processing, now widely referred to as "multitasking," for the major models. With the transition from single-processor supercomputers to multiprocessor supercomputers such as the CRAY X-MP, parallel processing became generally available. However, because it increased the level of difficulty, most scientists simply used these machines as single processors and were able to enjoy the capacity increase provided by four processors. A few major models have been converted and successfully operated in parallel on the X-MP/48. To facilitate the use of parallel processing, SCD offers favorable charging, special job classes, algorithms, consulting expertise, and a supportive management philosophy.

The center’s resources are subject to peer allocation and control. The SCD Advisory Panel meets twice a year. It is composed of scientists familiar with the proposed problems and the numerical techniques needed for their solution.

In 1986, a committee was formed to develop guidelines for the future directions of the NCAR supercomputing environment. The committee's report entitled "UCAR and NCAR Strategies in Supercomputing" [2] recommended: "1) focus SCD on large simulations and datasets; 2) assess
technology and prepare for future systems; 3) expand distributed computing; 4) take an active role in the national data communications effort; 5) help develop a National Geosciences Data System; 6) provide a balanced, effective computational environment; and 7) develop additional funding strategies to enhance the total NCAR-university computing environment to fully meet the needs of the atmospheric, ocean, and related sciences." SCD's activities as related to items two through seven are covered in section 3 "The Scientific Computing Division." Overall SCD is in close compliance with these recommendations.

1.4 Other Issues

In section 4, we discuss availability of computing resources at other centers as well as trends in minisupercomputer and powerful single-user workstations. In aggregate the computing requirements of the projects in this document far exceed the amount of computing time that we can expect to get at other centers. Individually, most of the simulations described herein exceed the capability of future workstations.

1.5 Summary

With a next generation supercomputer, machines that are at least one to two orders of magnitude more powerful than present state-of-the-art supercomputers, this community can bring an exciting and important set of problems across the threshold of solvability. These problems will require a factor of eight to satisfy the need for increased resolution. Factors of 9 to 30 will be required by the 1990 timeframe for simulations of cloud entrainment processes, turbulent boundary layer flows involving clouds, and mesoscale convective systems. Models which simulate the coupling of oceans and atmospheres will require at least an order of magnitude increase in computational capability.
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The NCAR Scientific Computing Division provides a computing facility that is tailored to community's needs. SCD is well poised – both in technology and expertise – to support a next generation supercomputer.
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2. FUTURE SCIENTIFIC REQUIREMENTS

2.1 Cloud and Mesoscale Dynamics
(T. Clark, K. Droegemeier, W. Cotton, R. Pielke)

2.1.1 Introduction

The science of clouds and mesoscale meteorology spans a range of scales from cloud droplets of a few micrometers in diameter through weather phenomena such as precipitation bands in tropical and extratropical cyclones of a few hundred kilometers in scale, and mesoscale convective systems of several hundred kilometers in diameter. The computing needs of this community are enormous since mesoscale phenomena on scales of hundreds of kilometers are strongly affected by air motions and precipitation processes occurring on scales of a few kilometers or less. Likewise, cloud microphysical processes occurring on the scale of micrometers are strongly influenced by organized air motions and turbulence on much larger scales. Despite major progress in furthering our understanding of cloud and mesoscale phenomena, current models consist of rather crude parameterizations of smaller-scale phenomena such as turbulence, cloud-scale transports and energetics, precipitation processes, electrical effects, and radiative processes. To put the science of clouds and mesoscale meteorology on a more solid foundation, major advances in computer resources will be required to allow more realistic treatments of smaller-scale dynamics and physical processes, and at the same time allow interactions with larger-scale weather systems.

2.1.2 Progress in the Past Decade

The past decade has been noted for enormous advances in the development and application of cloud-scale and mesoscale models. Some examples of results made possible by computing on the CRAY X-MP include:
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- High-resolution simulations of explosive marine cyclogenesis (surface pressure drops 10 millibars in 6 hours) using grid sizes of 40 kilometers (Km) and a mesh size of 91 x 121 x 15 have provided an understanding of the fine-scale structure of this type of storm.

- Results from 3-D numerical cloud model simulations requiring the memory and disk space available on the X-MP have provided advances in our understanding of squall lines.

- Fine-resolution large-eddy simulations (LES) of boundary-layer turbulence and stratocumulus clouds have provided more detailed information on turbulent flow structure and physics of those clouds. Such simulations require approximately 2 Megawords (Mwds) of memory and 31 Mwds of Solid-state Storage Device (SSD) storage.

- Some of the first exploratory multiscale interaction simulations of the growth and decay of mesoscale convective systems have been performed in two and three dimensions with explicitly-resolved cloud-scale motions. These simulations have advanced our understanding of processes involved in the formation of squall line structures, the genesis of mesoscale convective systems, and the evolution of mature mesoscale convective complexes.

- Major advances in the fundamental physics of the atmosphere's flow response to topography have been made through the simulation of up-slope and orographic snowstorms, the influence of terrain on typhoon dynamics, the simulation of thermally-forced flows and the role of thermally-forced circulations on the genesis of inertially stable mesoscale vortices over the Rocky Mountains, the simulation of Hawaiian rainbands, and the Denver convergence zone. Moreover, an important input required in general circulation models (GCMs) to improve weather predictions is the response to stratified flow over topography. Many types of phenomena are involved such as strong downslope winds produced by the excitation of gravity waves in the lee of mountain ranges, rainbands.
formed on the upwind side of isolated islands due to the impinging flow of very stable air (low Froude number), or the summertime convective regimes which are strongly influenced by the interactions between the air and the topography. Understandably, the flows which result in severe downslope windstorms are important to improve local weather forecasts. They are also important in predictions of large-scale circulations because of the interaction between the gravity waves and mean flow. GCMs are showing that gravity wave drag parameterizations are an important consideration. Large-eddy simulations (LES) of severe downslope windstorms and pressure drag calculations have just begun to become feasible in three dimensions, as they require high horizontal and vertical resolution using nonhydrostatic models.

- The behavior of cumulus cloud fields has been studied using two- and three-dimensional explicit simulations of populations of shallow and deep convective clouds. Statistical analysis of cloud field simulations will be useful in testing and developing cumulus parameterization schemes.

- Great strides have been made during the past ten years in understanding thunderstorms, including factors contributing to rotating storms, microburst formation, hail formation, and storm propagation.

2.1.3 Examples of Scientific Areas in Cloud and Mesoscale Meteorology that Require an Increase in Computer Power and Resources

- **Entrainment Processes.** The simulation of detailed entrainment processes in cumulus clouds requires a substantial increase in computer power. Limited high-resolution simulations of entrainment have been performed in two and three dimensions. To examine entrainment processes in sheared flow in three dimensions will require an expansion in computer capability by at least a factor of ten. These simulations are one of the basic keys

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in developing the scientific understanding of the detailed coupling of cloud microphysics and cloud dynamics that in turn is important for understanding the chemistry of clouds and the formation of precipitation.

- **Simulation of Large-eddy Turbulence.** The simulation of the turbulent planetary boundary layer through the large-eddy simulation approach, including the effects of cloud and radiation processes, requires an increase in power by at least a factor of ten. These simulations are vital to further understand the physics of stratocumulus cloud formation and dissipation. Higher spatial resolution is essential for realistic simulations of the stable and neutral boundary layer, as well as for accurate representations of entrainment across the top of the convectively mixed boundary layer ($\Delta \sim 2m$). Moreover, simulations of the influence of inhomogeneous surface conditions on boundary layer processes require larger domain sizes, including telescoping interactive grids to minimize lateral boundary contamination. Advances in computer power will allow the application of the LES approach to the simulation of middle-level clouds and cirrus clouds including large-scale lifting processes and explicitly simulating turbulent air motions driven by shear, radiation, and precipitation processes. The results of these simulations will help produce more realistic parameterizations of these processes in general circulation models.

- **Mesoscale Convective Systems.** An increase in computer power by a factor of ten is necessary to permit three-dimensional simulations of multiscale interaction in the growth and decay of mesoscale convective systems and the manifestation of major outbreaks of severe weather and heavy rainfall. The advent of new operational observing systems (NEXRAD, wind profilers, automated surface stations and GOESNEXT) in addition to STORM specialized field programs, will provide mesoscale datasets having unprecedented detail that can be used for both model initialization and verification.
• **Topographically Influenced Flow.** An increase in computational power by a factor of ten is required for improved simulations of airflow over mountain complexes and to significantly advance our understanding of such wave mean flow interactions. Improved parameterizations of mountain drag for weather prediction models will be a direct benefit of such studies. In the case of very stable (low Froude) number flow over isolated obstacles, simulations of the atmosphere's flow response to topography have led to significant advances in understanding the fundamentals of such low Froude number fluid dynamics. There are many scales of interaction that to date have been underresolved: An increase in computer power by a factor of ten would greatly increase the realism of this type of calculation and would have important impacts on our ability to improve local (particularly coastal or winter time) predictions in mountainous regions. Regions as large as 500 km on a side are necessary to capture the general barrier dynamics of the flow along Colorado's Front Range, for example, where grid sizes of about 1 km are required to resolve the scale selection mechanisms producing the cloud fields. An increase in computing power by a factor of ten is crucial to this problem. Calculations of this type, with better resolution, will for the first time allow meaningful tests of the predictability of mesoscale flows. It is hypothesized that the strong local forcings that exist on these scales should favorably affect predictability. In addition, it appears that these last two phenomena provide an ideal opportunity to study the interactions between mesoscale processes and cloud microphysics, an area of physics that is ripe for attack.

• **Convective Cloud Field Simulations.** The explicit simulation of the behavior of a realistic convective cloud field over a large area is essential for developing parameterizations for general circulation models and operational forecast models. Calculations including both deep and shallow convection will require about a factor of 100 increase in computer power available over that on the CRAY X-MP/48. With a factor of 10 increase in power, a few community-type exploratory cloud field calculations can be accomplished.
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- **Turbulence.** In the area of direct numerical simulations of turbulence, it is now possible to reach the Reynolds number scaling regime characteristic of fully developed turbulence with homogeneous simulations. Present calculations indicate that a factor of ten increase in computing power will allow convection calculations with realistic boundaries to reach this regime. If Reynolds numbers several orders of magnitude below atmospheric Reynolds numbers can be reached, laboratory experiments indicate that several effects that might be caused by viscous instabilities in the boundary layer that are suppressed by large-eddy simulation. With each increase in computing power, increasingly complex boundaries can be studied by direct techniques.

- **Air Quality.** The realistic simulation of atmospheric and terrestrial effects due to air pollution includes the modeling of mesoscale and regional meteorology on both short and long terms, the modeling of the dispersion of point and area sources of pollutants, and the modeling of the deposition and chemical transformation of the pollution. Thus, not only must the mesoscale processes discussed above be represented, but separate models for dispersion and air chemistry must be included. The dispersion model approaches have utilized both Eulerian grid models and Lagrangian dispersion models. The Eulerian method requires conservation equations for each relevant chemical species that must be solved within a grid mesh comparable to the meteorological model. The Lagrangian dispersion model includes the release of thousands of particles that are transported and mixed by modeled meteorological conditions, with a linked chemical species model based on concentrations of each species used to calculate the chemical deposition and transformation.

Computer requirements include those needed to simulate the mesoscale phenomena described above plus chemistry and dispersion calculations. The addition of chemistry can magnify the computational requirements for the simulation of atmospheric flows of mesoscale atmospheric flows alone by a factor of three to ten times or more.
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- **Land Use Variability.** It is clear that realistic climate and climate change scenarios must account for the cumulative effect of mesoscale weather phenomena, both surface constrained and propagating. Local land use variability, for example, as contrasted with assuming surface homogeneity over a General Circulation Model (GCM) grid cell, can exert major impacts on the partitioning of heat energy into sensible and latent heat fluxes, as shown during the Convection Initiation and Downburst Experiment (CINDE) program, as well as on the total net radiation through different values of the land surface albedo. When vegetation is present, realistic representation of canopy conductance is required. To investigate the influence of mesoscale land use and propagating atmospheric systems on climate, a variety of different geographic areas must be simulated for an annual cycle. (Alternatively, although impractical, a GCM could be integrated with mesoscale resolution over the same period). To simulate a representative number of geographic sites would necessitate a proportionately larger number of model runs.

- **Severe Thunderstorms.** At least a factor of ten increase in computer power is needed to simulate simultaneously a rotating thunderstorm and the genesis of tornadic vorticies. Likewise, such computer power is needed to simulate the physics of hail growth, thunderstorm electrification processes, and processes responsible for severe surface winds, downbursts, and flash floods.

- **Assimilation/Forecast Research.** The implementation of numerical mesoscale forecast models requires the invention, development and testing of algorithms for analysis and assimilation of a mix of data from sources such as radar wind profiler, Doppler radar, and automated surface data acquisition systems. Such research requires convenient access to the multiplicity of data sources and sufficient computer power to develop and exercise the analysis and assimilation algorithms. Techniques such as the adjoint method require considerable parallelism in the code and faster computers to be operationally useful. In addition, major advances in mesoscale forecasting technology can only come from
prototype operational forecasting in which one or more mesoscale models are run daily for selected periods. This will require access to dedicated blocks of supercomputer time.

- **Predictability.** The predictability of individual thunderstorms and other mesoscale weather events is an important component of forecasting research. Greatly expanded computer power is needed to assess the inherent predictability of such convective mesoscale events. The procedure involves performing a set of numerical experiments in which the impact of the inherent uncertainty of observed initial conditions, boundary conditions, and model physics is imposed on a model to examine the uniqueness of mesoscale model predictions.

2.1.4 Overall Computer Requirements

Table 1 summarizes the anticipated computer requirements for cloud and mesoscale research in the next five years. In all, mesoscale research require nearly 250,000 CPU hours per year of a single CRAY X-MP processor.
<table>
<thead>
<tr>
<th>Task</th>
<th>X-MP Single Processor Hours/Run</th>
<th>Number of Runs/Year Per Group</th>
<th>Memory Required</th>
<th>Number of Groups*</th>
<th>Total K hrs/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cumulus Entrainment Processes</td>
<td>50-500</td>
<td>10</td>
<td>100M</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>2. Simulation of Large-eddy Turbulence</td>
<td>50-100</td>
<td>25</td>
<td>150M</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>3. Mesoscale Convective Systems</td>
<td>100-200</td>
<td>5</td>
<td>100M</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>4. Topographically-influenced Flow</td>
<td>20-100</td>
<td>10</td>
<td>50M</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>5. Convective Cloud Field Simulation</td>
<td>100-200</td>
<td>25</td>
<td>100M</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>6. Turbulence</td>
<td>400-800</td>
<td>10</td>
<td>400M</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>7. Air Quality</td>
<td>300-600</td>
<td>5</td>
<td>150M</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>8. Land-use Variability</td>
<td>20-100</td>
<td>20</td>
<td>50M</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>9. Severe Thunderstorms</td>
<td>100-200</td>
<td>25</td>
<td>100M</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>10. Assimilation</td>
<td>50-100</td>
<td>15</td>
<td>50M</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>11. Forecast Research</td>
<td>1-2</td>
<td>365</td>
<td>10M</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>12. Predictability</td>
<td>50-100</td>
<td>30</td>
<td>100M</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Overall annual requirement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>247</td>
</tr>
</tbody>
</table>

* research groups involved

Table 1. Mesoscale computer requirements
2.2 Climate

(Redrafted by Warren Washington)

The study of climate and global change has received as much national and international attention in the past few years as any area of scientific research. Interest in reliable regional predictions for the next month, season, year, and century has grown among policy makers in the United States and other countries. Great interest has been expressed in studies to determine the impact on the global climate of rising concentrations of carbon dioxide (CO2) and other trace gases and particles. Concern is growing that we may be permanently and deleteriously changing the earth's climate.

The scientific community’s emphasis on global-change research has likewise increased. More scientists are recognizing that geophysical modeling has reached a state where, over a period of one or two decades, models will be useful in predicting regional global change a month to a season in advance, in determining the effect on climate of various human activities, and in furthering our understanding of longer-term climate trends.

Although the new Earth Observing System (Eos) and other observational systems will soon be available, and although climate research will require enormous computation capability, computing resources are increasingly limited. The number of questions that can be satisfactorily answered only through experiments using comprehensive coupled atmospheric-oceanic chemical and biological models is increasing rapidly, as noted in the UCAR Climate Systems Modeling Initiative (CSMI). In addition, sensitivity and scenario experiments will have to be extended over a much larger number of cases and/or over a longer time interval (on the order of a century). The availability of expanded computing resources at NCAR will result in a significant increase in university scientists involved in global-change simulation and climate sensitivity studies to attack these scientifically attractive and significant questions. With developments in the extensive diagnostic calculations necessary to interpret the results of climate model simulations and the need
to assemble new global climate datasets from conventional and satellite observations, climate
research in the next decade will necessitate substantially increased computer resources.

2.2.1 Science Made Possible by the CRAY X-MP/48

- Development and use of the Community Climate Model (CCM) have resulted in an increase
of users and an unexpected spread of the CCM to other climate centers (now over 40
projects, see Attachment B). The model and its many versions are being used to study an
increasing number of climate problems.

- Scientists completed evaluations and intercomparisons of the National Meteorological
Center (NMC) and European Centre for Medium Range Weather Forecasts (ECMWF) data
analyses. This work will allow objective comparison between the two datasets as well as
climate models. The data are available to the Scientific Computing Division user
community.

- Scientists successfully coupled a global version of the CCM to a global ocean model. After
30 years of simulation, the results indicated a globally averaged surface air temperature
increase of 1.6 degrees C for instantaneously doubled CO₂, whereas for a 1% increase of
CO₂ per year the temperature increased by 0.7 degrees C. The simulation in the tropical
Pacific showed, for the first time, warm and cold events similar to those found in the
observed El Niño and La Niña sequence.

- Research indicated that the CCM response to an imposed Antarctic ozone hole was
radiatively governed, suggesting that dynamics play only a small role in the formation and
maintenance of the ozone hole.
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- In regional climate studies, scientists have successfully coupled the NCAR mesoscale model to the CCM. Results showed remarkably realistic regional simulations.

2.2.2 Research Problem Areas

Five areas of climate research are expected to change rapidly in the next decade within the community of university and NCAR scientists; these areas are closely related to environmental issues of increasing national and international concern. The opportunities for addressing these national concerns will go largely untapped, however, unless necessary computer resources are provided. Brief comments on each of these areas are presented below, with emphasis on their use of computer-intensive climate models.

2.2.2.1 Seasonal Climate Prediction

The national welfare and economy would benefit significantly from improvements in forecasting the coming season's climate (e.g., wet/dry, cold/warm). Research to improve such monthly and seasonal forecasts was prescribed by the U.S. Congress in the National Climate Program Act of 1978. Skill in such predictions, as currently exhibited by combined statistical-empirical methods, is still quite poor. Further exploration of the potential of such predictions with climate models has begun, but is hampered by insufficient computing resources.

One of the most important developments in climate research in the last decade or so has been the apparent global-scale teleconnections between conditions in the equatorial upper ocean and atmospheric circulations in middle latitudes. Relatively warm (El Niño) or cold (La Niña) water in the central equatorial Pacific may be related to the occurrence of anomalous atmospheric patterns over the United States. This interaction, recently identified as part of the so-called Southern Oscillation involving higher-latitude responses, encompasses a large fraction of the tropical ocean and global atmosphere.
Understanding these events is the objective of intensive theoretical, empirical, and modeling research by government, university, and NCAR scientists. This research will assist in designing future effective observing and/or monitoring systems to study global climate change. Applying this understanding to operational seasonal forecasting in five to ten years' time, however, will require better models, conventional and satellite data acquisition systems, and a level of computing support not currently available.

For viable seasonal climate predictions, it is also necessary to know the current state of the climate system including the atmosphere, the upper ocean, soil moisture, and snow and ice cover. Since enormous volumes of data are involved, especially from satellites, analysis of global observational datasets from satellite and conventional sources is essential for climate models as initial conditions and for model validation.

Studies over the last several years have clarified the dependence of monthly and seasonal climate anomalies on ocean surface temperature anomalies. As previously noted, the largest influence comes from the tropical oceans and, therefore, coupled ocean-atmosphere models that can forecast ocean surface temperatures will be required for useful seasonal forecasting. Models capable of predicting the impact of other physical processes such as soil moisture, snow cover, vegetation, chemical and biological activity, on time scales of a month, season, and year, will also be needed.

Coupled atmosphere-ocean models will 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 initial and/or boundary conditions.) Seasonal forecast models will not only entail many integrations, but they may also eventually require high resolution (e.g., 100 x 100 km in the horizontal and 15 or more vertical layers) to resolve the regional details.
2.2.2.2 Climatic Effects of CO₂ and Other Trace Gases

The possible global and regional climatic effects of increasing levels of CO₂ and other trace gases in the atmosphere (principally the result of the consumption of fossil fuels) are receiving a great deal of attention. In the past few years, about a dozen models have been applied to this problem and simulations are under way with several different general circulation models (GCMs) to explore the atmospheric and oceanic effects of increased CO₂. Although all models show a general warming, there is little agreement on the accompanying changes of cloudiness, precipitation, and surface moisture in various regions of the world. Simulations over a century or more using GCMs are 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 regional agricultural and economic impacts.

The climatic effects of rising levels of atmospheric trace gases, especially chlorofluoromethanes and tropospheric ozone, need comparable attention. The collective warming effect of all such gases is, perhaps, 50% to 100% of that due to CO₂ alone. Sensitivity experiments are necessary to establish whether or not the climate change resulting from 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 for this work are additional to the requirements for related studies described Section 2.3, Atmospheric Chemistry.)

The ocean plays a major role in the CO₂ climate problem by virtue of its high heat capacity (slow thermal response) and through its direct role in the carbon cycle by absorption and subsequent transformation of CO₂. To determine authoritatively the climatic impacts of CO₂ and possibly of other trace gases, it will be necessary to have further studies with a more refined coupled ocean-atmosphere system and to use various scenarios that assume different gradual increases in atmospheric CO₂ over several decades, rather than the sudden doubling or quadrupling now used. Integrations of coupled atmosphere-ocean GCMs will have to be carried out over a century or
more and will require substantial computer resources. Scientists now involved in this research could usefully employ a substantial fraction of a CRAY Y-MP.

2.2.2.3 Paleoclimates

The simulation of paleoclimates by numerical models is a unique opportunity for calibration of the models and for providing important information on the behavior of the climate system. Past research with NCAR computing facilities has involved simple models or, in the case of the ice-age climate of the last ice age, atmospheric GCMs. The earth's climate experienced several glaciations in Pleistocene times in apparent response to the variations in orbital parameters, and geological evidence is rapidly accumulating that the climate has changed in response to the changing distribution of oceans and continents over geological time ranges.

The systematic simulation of paleoclimates is an important goal for the university community and NCAR over the next decade. A new area, and one of the fastest growing in new-investigation territory, its exploration will yield valuable insight into the general nature of climate systems. 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. 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 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 forced by the temporally fixed climate. Such a program will require extensive computer resources over the next decade.

2.2.2.4 Regional Climates
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Relating regional-scale climate (e.g., on scales of 100 km or less) to large-scale climate (e.g., on scales of 5,000 km) is a critical element of climate research and of great practical interest. The impacts of climate and climatic change, after all, are felt on the local scale. Without the ability to translate climatic information from the large scale to the regional scale, the results of models with only large-scale resolution are 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, we are now able to study interactions between a regional or mesoscale model and the CCM. With the increasing emphasis on modeling mesoscale atmospheric phenomena, its application to regional climate has become a new and important research frontier. Although emphasis at first may be on the climate of the United States, this approach would also be useful for studying monsoon systems and the effects of land-use changes in tropical forest areas. Computer resources must be provided to further improve on one-way versus two-way mesoscale coupling to the large scale and to develop an extended experimental program with a variety of model physics formulations. This approach may also provide regional detail in the climate change from increasing CO2 or in seasonal climate forecasts. However, if mesoscale models are to achieve computational stability, short time steps (e.g., of a few minutes or less), are needed and the computing demands are large.

2.2.2.5 Improved Model Parameterizations

To support the climate model applications described above, efforts must be renewed during the next decade to improve the parameterizations of those physical processes likely to be essential to climate-sensitivity studies and climate prediction. Key processes are the hydrological cycle (precipitation and cloud formations), land-vegetation surface effects, boundary-layer exchanges over sea, and land, ice and snow, cloud-radiation feedbacks, and orographic and subgrid-scale turbulent effects. The exploration of each of these effects commands increased computer resources for the sensitivity and resolution studies.
Land-surface processes needing attention include the interactive modeling of biomass growth, modeling the effects of vegetation on friction, run-off, and 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 over paleoclimatic time scales.

Cloud-radiation feedback processes needing attention, in addition to microphysics, include the development of improved algorithms for (1) cloud formation, (2) the effective absorbing, reflecting, and scattering properties of clouds in terms of their liquid-water content and drop-size distribution, and (3) the effects of cloud height and thickness on the ambient temperature, moisture, and vertical motion. Such parameterizations are key to the improvement of the simulation of the net radiative effects of large-scale cloudiness and, hence, to the maintenance of the planetary heat balance. Research on high-level cirrus and low-level stratus will require extensive model sensitivity tests to effectively use the satellite radiance data to be collected in the next five to ten years as part of Eos. In conjunction with these studies, more scrutiny is needed of the details of other hydrologic processes, especially precipitation.

Representation of orographic effects in climate models needs improvement, since it has a profound influence on the quasistationary and transient behavior of the atmospheric circulations on both the mesoscale and the planetary or large scale. Extensive numerical experimentation with improved orographic treatment in GCMs will be required for the models' successful application in weather forecasting and climate simulations.

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2.2.3 Summary of Computing Requirements

Decadal, high-resolution, coupled climate simulations resulting in reliable predictions of global and regional climate changes will require supercomputers with one to two orders of magnitude more computing capability than the X-MP/48. Table 2 projects the annual resources needed by each of the projects described in the climate section.

<table>
<thead>
<tr>
<th>Projects</th>
<th>Memory in Mwds</th>
<th>Simulated Time/Run (years)</th>
<th>CPU Hours/Year</th>
<th>CPU Hours/Experiment</th>
<th>Number of Experiments/Year</th>
<th>Total CPU Hrs (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal climate prediction</td>
<td>16</td>
<td>5+</td>
<td>65</td>
<td>365</td>
<td>7</td>
<td>2.6</td>
</tr>
<tr>
<td>Climatic effects of CO₂ and Trace Gases</td>
<td>50</td>
<td>100</td>
<td>130</td>
<td>13,000</td>
<td>5</td>
<td>65.0</td>
</tr>
<tr>
<td>Paleoclimates</td>
<td>50</td>
<td>100</td>
<td>130</td>
<td>13,000</td>
<td>5</td>
<td>65.0</td>
</tr>
<tr>
<td>Regional climates</td>
<td>16</td>
<td>5+</td>
<td>65</td>
<td>365</td>
<td>3</td>
<td>1.1</td>
</tr>
<tr>
<td>Model parameterizations</td>
<td>80</td>
<td>100</td>
<td>200</td>
<td>20,000</td>
<td>10</td>
<td>200.0</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>334.0</strong></td>
</tr>
</tbody>
</table>

*Table 2. Required computing resources for climate research*

Notes: Table 2 assumes T42 resolution with 12 levels Hrs; Exec/Model year is based on a single CRAY X-MP processor.

Figure 3 shows past and future computer capabilities compared with 3-D atmospheric climate modeling speed and memory requirements.
Figure 3. Computer capabilities compared with 3-D atmospheric climate modeling speed and memory requirements.
2.3 Atmospheric Chemistry

(Guy Brasseur)

Public concern about environmental, climatic, and economic issues have been some of the driving forces behind the rapid increase in atmospheric chemistry research. During the past decade, many scientists have been involved in attacking the basic and applied questions related to the impact of human activity on the chemistry of the atmosphere, particularly the stability of the stratospheric ozone layer, the formation of acid rain, and global warming due to "greenhouse gases." Today, much attention is given to the biogeochemical cycles and their role in the climate system. Atmospheric chemistry is an essential component of the earth's system and its links to questions related to "global changes" are evident.

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 reliable information for policymakers still lies in the future. Furthermore, the role of different chemical constituents in potential climatic changes as a result of "the greenhouse effect" needs to be clarified. 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 applied studies by the NCAR/university community. These modeling activities are expected to require large increases in computer resources in the near future. Similarly, the analysis of large datasets generated by satellite remote-sensing techniques will make sizable demands on computing resources. In this section, we discuss several research areas that will require expanded computational power if they are to be pursued at all. These areas are of great interest to the scientific community, are of considerable practical importance in dealing with national concerns, and are intrinsically so.
complex that less computer-intensive approaches are not likely to achieve the basic goals of these problem areas.

The purpose of this exercise is not to devise a plan for allocating already limited computer resources, but to develop the rationale to justify the hardware acquisition necessary to meet future requirements for the entire atmospheric community. In considering future computing requirements, it is essential to thoroughly consider 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 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. The estimates of computer requirements in this section assume that such institutional arrangements will be conceived and instituted to the extent required to achieve efficient use of resources. These estimates for simplicity also assume the use of a single processor on the CRAY X-MP, although multitasking will in all probability be adopted.

2.3.1 Modeling Remote Global Tropospheric Chemistry

The chemistry of the global-scale troposphere will receive increasing attention over the next decade. We currently have the ability to measure concentrations of trace gases as low as a few parts per trillion by volume. Systematic observations since 1958 are available for carbon dioxide (CO₂) at a number of sites and over the past decade for fluorocarbons (CF₂Cl₂ and CFC₃), methyl chloroform (CH₃CCl₃), and nitrous oxide (N₂O). We anticipate that the database will expand in the years to come and that other gases, such as methane (CH₄), carbon monoxide (CO), and oxides of nitrogen (NOₓ) will be added to the list of measured species. Instrumentation has also
been developed 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 and climate system. Questions now being addressed include the following: (1) To what extent is the well documented rise in worldwide atmospheric CO₂ due to burning of fossil fuel and how are CO₂ concentrations modulated by changing land-use practices and slash-burn agriculture? (2) What are the consequences of the observed increases in CH₄? (3) What are the processes that control NOₓ in the natural tropospheric environment and how are they disturbed by urban and agricultural emissions? (4) What factors regulate tropospheric ozone (O₃) in the absence of human activity? (5) How is O₃ disturbed by industrial sources of NOₓ and hydrocarbons or by aircraft? (6) What are the essential features of the natural sulfur cycle in the troposphere? and (7) What processes control the production and distribution of aerosols and the chemistry of precipitation, particularly acid precipitation?

To answer 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. A very important first step is the integration of realistic chemistry into global circulation and climate models. Among the complicating factors are the following: (1) important chemical elements of the troposphere are not in local chemical equilibrium; (2) transport plays an important role in distributing chemical species whose lifetimes range from days (e.g., sulfur dioxide) to weeks (NOₓ) to months (CO); (3) the wide range of lifetimes poses difficulties for the description of their distribution requiring a complex transport model, and (4) 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 such as the CCM is
needed. Such a model would have a horizontal resolution of approximately 2 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, to account for the removal of particular species in the stratosphere (CFCl2, CFC13, methyl chloride, and CH3CCl3, for example) and to account for downward transport of radicals such as NO and O3. Model runs of approximately two years' time will be necessary. Other chemical models with simplified meteorological coupling will also be required.

2.3.2 Introduction of a Detailed Chemical Code in the NCAR CCM

The understanding of the major couplings occurring in the atmosphere, and more generally, the description of the climate system requires that detailed formulations of chemical processes be introduced in global circulation models. A chemical scheme developed by ACD scientists with roughly 15 to 20 transported species and about 20 to 30 fast reacting compounds will be coupled to the semi-Lagrangian transport model developed for the CCM by the Climate and Global Dynamics Division (CGD) staff.

The first tests of the chemical/transport model (CTM) will be performed offline while the ultimate goal is to include the chemistry online in the NCAR stratospheric/tropospheric version of the CCM (T42 resolution with 30 levels). A convective scheme will be included to account for rapid vertical transport in the troposphere. The photodisassociation rates will be parameterized following studies made with detailed radiative codes.

At the level of complexity considered in the present project, it is estimated that one day simulation on the CRAY X-MP will require about one hour CPU time. A typical model simulation will involve integrations over periods of three to five years.
2.3.3 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 chemical 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 to integrate and understand the complex interactions among all the processes involved.

For the past decade, one-dimensional (1-D) stratospheric photochemical models have played a central role in developing our knowledge of the stratospheric ozone layer and in predicting future changes to the global ozone column. These models include a parameterized vertical transport prescription, detailed descriptions of the photochemistry, and sometimes a reasonably detailed radiation-temperature submodel. The computation time per experimental run ranges from a half-minute to several minutes of equivalent Cray central processing unit (CPU) time, depending on the complexity and structure of the individual model. However, the next important steps toward reducing uncertainties in model predictions of anthropogenic perturbations of the 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 multidimensional 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 (1) the quantification of solar-induced or dynamically-driven natural variations in ozone distribution; (2) the sources, sinks, and distribution of water vapor; (3) the global distribution of other trace species, including ozone; (4) the transport of manmade pollutants and their impact on the atmosphere; (5) stratospheric and tropospheric exchange processes for both inert and reactive trace species; and (6) 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 one used at NCAR including mean Lagrangian transport, turbulent mixing, and full chemistry) has about 35 latitudinal zones, 80 vertical layers, and more than 40 trace species and 120 reactions. The model requires about one hour of Cray CPU time per 20 model years. For many problems, such as the impact of manmade pollutants, simulation runs will typically require 5 CPU hours per 100 years of simulation.

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 by existing 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 may 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. Obviously, such a three-dimensional model is beyond the currently available computing capability.
2.3.4 Regional Modeling and the "Master Mechanism"

Public and scientific concerns about regional air quality and long-range transport of air pollutants began in the 1950s in Europe when chemical analysis of rain and snow indicated transport of air pollutants (such as sulfate) from western Europe into Scandinavia. The same concerns have been evident in the United States and Canada for the past 20 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.

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, the factors are too poorly understood. For example, while elevated oxidant levels (O3 and some NOx) are often found over multistate regions, we are ignorant about the processes that limit the rates at which these oxidants are produced, discharged, or where in the atmosphere the processes occur.

Key questions of regional air quality include the following: (1) What are the sources and sinks of ozone? (2) How is non-urban ozone affected by anthropogenic activities? (3) What are the major processes that oxidize sulfur and nitrogen compounds to sulfate and nitrate? (4) How far is the acidic material transported? (5) Given the answer to these questions, what then is the source-receptor relationship in the emission and deposition of acidic material? (6) What is the impact on atmospheric aerosol concentrations, visibility, and radiation due to anthropogenic activities? The scope of research for these questions ranges from the urban scale to major portions of a continent. They also include extensive efforts to understand the basic chemical modeling and to quantify the relative importance of the various chemical paths involved.

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 precipitation are a major task. Another important task is the development of comprehensive models (such as the Master Mechanism including 5000 reactions) that simulate the chemical and photochemical mechanisms occurring in the boundary layer and in the free troposphere. 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 to 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.

2.3.5 Planetary Atmosphere Models

Much of our current knowledge about the atmospheres of the planets has been developed over the last ten years as a consequence of the National Aeronautics and Space Administration’s (NASA) planetary exploration program. Some studies of planetary atmospheres, especially Venus and Mars, have successfully used the NCAR Cray during 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 extremely large. Rather modest modeling efforts, the sum of which could place a considerable demand on NCAR computing resources, will develop.

2.3.6 Satellite Data Processing and Analysis

The techniques developed in the late 1970s and 1980s to observe the composition and dynamics of the atmosphere from satellites have greatly improved our knowledge of the global behavior of various important chemical constituents in the middle atmosphere. 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 fields of temperature
derived from satellite observations, they have also been able to calculate winds and the transport of heat and momentum in the upper atmosphere. The supercomputers at NCAR have been especially useful in this work, particularly in supporting analysis and handling the associated large dataset, graphics and visualization capabilities, and the detailed calculations required for designing these experiments. During the next decade, several satellite experiments are expected to provide more refined vertical and horizontal resolution and longer time spans of global measurements for many additional trace constituents important to understanding and assessing global change. ACD will be heavily involved with these initiatives. The Upper Atmosphere Research Satellite (UARS) to be launched in the 1990-91 time frame will produce a dataset more than an order of magnitude larger than that for the Limb Infrared Monitor of the Stratosphere (LIMS) experiment with which we were heavily involved. In addition, three experiments for the Earth Observing System with substantial ACD involvement are entering the definition phase. These are expected to be launched in the 1996-98 time frame and will continue operations for 10 to 15 years.

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 for work requiring interaction with multidimensional chemical/dynamical models. In addition, the Eos work will require considerable calculation to support experiment design and implementation.
2.3.7 Summary of Computer Requirements

The requirements for computing power discussed in this section are given below in units of thousands of CRA Y X-MP CPU hours:

<table>
<thead>
<tr>
<th>Subject</th>
<th>X-MP CPU Hours/Run</th>
<th>Number of Runs/Year</th>
<th>Memory per run</th>
<th>Total K hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropospheric Modeling</td>
<td>1500</td>
<td>26</td>
<td>20M</td>
<td>54.0</td>
</tr>
<tr>
<td>Stratospheric Global Models</td>
<td>5</td>
<td>24</td>
<td>3M</td>
<td>0.12</td>
</tr>
<tr>
<td>Regional Air Quality Modeling</td>
<td>1</td>
<td>100</td>
<td>4M</td>
<td>0.1</td>
</tr>
<tr>
<td>Planetary-Atmospheric Models</td>
<td>2</td>
<td>50</td>
<td>3M</td>
<td>0.1</td>
</tr>
<tr>
<td>Satellite Data Processing and Analysis</td>
<td>1</td>
<td>500</td>
<td>5M</td>
<td>0.5</td>
</tr>
<tr>
<td>Overall Annual Requirement</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>54.8</td>
</tr>
</tbody>
</table>

*Table 3. Computing power requirements*
2.4 Oceanography

(Bill Holland)

2.4.1 Introduction

A close relationship exists between the oceanographic and atmospheric sciences, particularly in the development and application of numerical models. Similar applications exist in geophysical fluid dynamics as well as numerical problems to be solved, because the oceanographic and atmospheric systems are really just sub-elements of the larger climate system. An increasing amount of the relevant problems in each field require the consideration of the coupled ocean-atmosphere system. For these reasons, the major computing resource available to the academic community for ocean modeling has been at NCAR, where a small but active oceanographic program is embedded in the larger program of climate research.

In the early 1980s, the computing needs of the oceanographic community were assessed [3]. At that time, it was suggested that ocean modeling was developing at such a rate and would take on such a central role in oceanographic research programs that large, dedicated computational resources would be required. These expectations were more than realized and today ocean models are key elements in such large and diverse programs as World Ocean Circulation Experiment (WOCE) and Tropical Oceans Global Atmosphere (TOGA). In fact, the recent Planning Document for WOCE Modeling (in draft form, March 1989) outlines just how far we have progressed along this track. Despite extraordinary progress, however, the most sophisticated models envisioned for the next decade do not yet exist and indeed will be a major product of the above programs. It is expected that such models will provide an overall synthesis of the observations from these experiments and will provide the foundation for models to fully realize the scientific objectives of these large ocean programs and climate studies. Thus, it is clear that even greater computer resources will be required for the decade of the 1990s to fully realize the scientific objectives of these large ocean programs and climate studies.

2.4.2 Progress in the Past Decade and Trends for the Future

Examples of results produced by the CRAY X-MP that were not possible with the CRAY-1A include:
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- The first experiment of the Community Modeling Effort (CME), a multiyear, multi-institutional, and multi-investigator program in ocean model development and applications, involved the first simulation of combined wind and thermohaline-driven, basin-scale ocean circulation that explicitly resolves mesoscale eddies (Bryan, Holland). The CME datasets are now under study by a number of researchers (see Attachment C).

- A global ocean calculation model that is marginally able to resolve eddies. This model was multitasked and effectively used the parallel capabilities of the CRAY X-MP/48 (Semtner, Chervin).

- Solutions of ocean circulation and turbulence that demonstrated the existence and nature of coherent structures in certain types of 3-D turbulence and the properties of balanced model solutions for both meso- and large-scale ocean circulation (McWilliams)

Enormous advances have been made in the development and application of sophisticated models of ocean circulation in the last decade. The availability of large computer resources has been crucially important to this task because of the requirement for high spatial resolution for the realistic treatment of mesoscale phenomena, including mesoscale eddies, western boundary currents, and narrow equatorial phenomena. In addition, many of the important time scales of variability are fast (the order of days) while simulations of long periods are required to understand the implications of such model results for climate purposes (the order of years to decades to centuries). For these reasons, various modeling groups at NCAR and elsewhere have found an every increasing need for very substantial computational resources. Several of the central themes in the advances of the last decade and the trends for the next one are outlined below.

2.4.2.1 Ocean General Circulation Models

In the early part of the decade, there were two classes of general circulation models: the so-called ocean general circulation models (OGCMs), which included much of the detail of the ocean (e.g., realistic coastlines, topography, observed winds, and thermohaline forcing) but no mesoscale eddies, and eddy-resolved general circulation models (EGCMs), which included higher horizontal resolution to allow for important mesoscale processes at the expense of physical simplicity and coarse vertical resolution. Today, these distinctions are blurred, as eddy-resolved models have become ever more realistic, including simulations of entire ocean basins for several decades, as in the WOCE-sponsored CME. Such experiments require hundreds of computer hours (CME#1
required 1500 CRAY X-MP single processor hours) and many such future experiments are needed to reap the benefit of improved ocean circulation simulation.

In the 1990s, eddy-resolving simulations of the global ocean will be needed. It is already clear that virtually all parts of the global ocean are intrinsically turbulent and that this turbulence cannot be simply parameterized. Given that realistic models of the global ocean are required for climate studies and as a tool for synthesis and understanding of WOCE global observations, a combination of fine spatial resolution (the order of 1/4 degree of latitude and longitude) and long duration integrations (seasonal, interannual, decadal) is necessary.

2.4.2.2 Equatorial Models

Circulation modeling of the tropical oceans is a rapidly expanding field of research and deserves separate mention. The connection between the state of the tropical ocean and the circulation in the global atmosphere is now known to be an intimate and powerful one, with important consequences for the earth's climate variability. Understanding this connection is being pursued both observationally and with sophisticated models. A number of different equatorial ocean models available to study this problem are now available at the Geophysical Fluid Dynamics Laboratory (GFDL), NCAR, and elsewhere. Coupled GCM runs are commencing at a number of institutions and many results from such models can be expected in the near future. The primary goal of the TOGA program is to have a coupled GCM predictive capability for the El Niño Southern Oscillation (ENSO) phenomenon. Meanwhile, the GFDL equatorial model is being used in a predictive mode at the National Meteorological Center (NMC). As yet, this project has not made use of coupled models but has used instead up-to-date NMC winds to force the model, and up-to-day measurements from the ocean for assimilation into the model. Such data assimilation efforts are in their infancy but will expand in the future to accommodate different kinds of data [e.g., Ocean Topography Experiment (TOPEX) altimeter data].

In the next several years, such models of multiyear, equatorial ocean variability will assume an operational capability, with sophisticated data assimilation techniques that can make use of the new satellite sources of synoptic surface data. Altimeter and very high resolution radiometer (AVHRR) sea surface temperature observations will be blended into the model. Scatterometers will be used to give a synoptic realization of the wind stresses for forcing the model to produce real-time predictions of the oceanic circulation and sea surface temperature field. Such predictions can be used in both coupled and decoupled models of the global atmosphere to allow predictions of global climate change. Large computer resources will be required for analyzing the observations and for developing and running such assimilative models. A decade of work will probably be needed to
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determine how best to accomplish this blending of observations and models to produce a "best" prediction of worldwide climate changes.

2.4.2.3 Regional Ocean Models

Very fine resolution models of small domains have evolved in the last few years to examine the details of local ocean circulation. Models such as the Gulf Stream and the California Current, as well as the inshore waters of the continental shelves, provide an alternative strategy to basin and global eddy models by allowing even better resolution to study and understand smaller-scale phenomena. In essence, the modelling compromise involves a trade-off between better resolution, on the one hand, and a need to know the inflows at the boundaries of the local domain, on the other. While such models, with a proper treatment of the open boundary conditions, are rather new on the scene, it is clear that only in this way can the oceanographic community link up to the multiplicity of important scales of oceanic variability.

In the next decade, a whole hierarchy of models, spanning regional to global domains, will be in use. These will be coupled together or embedded one within the other to correctly describe the connection between the larger and small scales of motion. The regional models will require computer resources on a scale comparable to the global models because of their enhanced resolution and detailed descriptions of local behavior. Such details are crucial for understanding such important local problems as ocean pollution and dumping, oil spills, fisheries management, ocean thermal energy conversion, and so forth.

2.4.2.4 Geophysical Fluid Dynamics

To understand the larger-scale systems described above, it is necessary to perform studies of important processes under idealized circumstances that isolate the essential elements and allow their study without the computational compromises that are required in more complete ocean models. Such studies can be computationally costly in their own right, either because many experiments are needed or because high resolution is essential. For example, in recent years models of turbulent processes on the scale of a few kilometers or less have led to improved understanding of basic mixing processes that can occur on the finest scales of ocean circulation. In the next decade, even better resolution is needed for such studies to elucidate the incredible richness of phenomena and behavior in a rotating, stratified fluid like the ocean.
2.4.2.5 Coupled Climate Models

In the last few years, coupled models of the atmosphere-ocean-ice system have been put to use to begin to address questions about the nature of climate variability and climate change on a whole host of time scales. These models have suggested "scenarios" of behavior of the greenhouse (increasing CO2) problem, for ENSO phenomena, for ice-age climate change, and for "nuclear winter" possibilities. Such models have been run with an ocean model component that is today considered a coarse resolution, rather simplified circulation model. The global and equatorial models described above that are needed for the next decade will allow many of these climate-related questions to be more carefully assessed and examined, with very substantial improvements in the reliability of our estimates of climate impacts. Equivalent improvements in the other components of the global climate system will also be required as we move toward highly realistic models of climate variability and models that can be used for accurate prediction of natural and man-induced climate change.

2.4.2.6 Satellite-derived Observations and Data Assimilation

As mentioned above, satellite systems that can synoptically map the global ocean will be present in the 1990s. Already, operational satellites, such as the various NOAA satellites, and experimental satellites, such as SEASAT and GEOSAT, have shown oceanographers an astounding new vision of upper ocean variability and its connection to atmospheric forcing. Future satellite systems, such as Topographic Ocean Experiment (TOPEX)/POSEIDON, NASA Scatterometer (N-SCAT), and Eos, will improve even more the ability to accurately observe the ocean synoptically.

These observations, as well as the new in-situ observing systems being developed for WOCE and TOGA, will create two new opportunities in ocean modeling research: (1) the blending of synoptic observations into ocean circulation models for prediction purposes, and (2) the critical testing of ocean models against independent observations. The large requirements in computational resources for developing effective assimilation schemes, particularly those that can merge surface observations with a model to realistically estimate the full three-dimensional circulation, have been mentioned above. Analyzing the vast quantities of data from these satellites, however, is also an enormous job, requiring large data storage and handling abilities as well as computational capacity. NCAR has pioneered such capabilities in both the atmospheric and oceanographic arenas, but will need a large enhancement in these areas to cope with the demands of the decade of the satellite.
2.4.3 Computer Resource Needs

As outlined above, ocean modeling research for the next few years will involve a continued vigorous expansion of effort and will require much greater computational resources than those currently available because: (1) models are becoming more sophisticated; (2) model studies are needing higher resolution; (3) more investigators are moving toward using large models; and (4) more kinds of problems are being attacked with numerical techniques. The manpower for carrying out these efforts, although still not as large as could effectively be used, is growing rapidly as a new generation of young Ph.D.s have developed their talents and an older group of established scientists not previously involved in numerical modeling have become interested in this topic. Further expansion will occur due to a growing appreciation of the need; for instance, a new NSF-sponsored postdoctoral program in ocean modeling is being administered by UCAR.

In this report, we cannot make the same careful assessment of computational needs that was carried out in the 1982 NRC report [3]. However, we can indicate a degree of the scale of this need by the following examples. During the decade of the 1980s, global ocean models have progressively improved their resolutions from 4 degrees latitude/longitude to 1/2 degree with comparable enhancements in vertical resolution. In the next five years, such models will use 1/3 degree and 1/6 degree resolutions to include the crucial effects of mesoscale processes. For basin scale calculations, the most recent ambitious numerical experiments have used 1/3 degree resolution but will progress to 1/6 and 1/12 degree resolutions in the next few years. For regional calculations, model studies currently using 1/6 degree resolution will progress to 1/12 and 1/24 degree resolution and even finer. Each of these factors of two enhancement requires eight times the computer power for a given length of simulation, all other things being equal. Thus, it is easy to see that even at the current level of effort, in terms of numbers of people and numbers of projects, that the oceanographic modeling community could well use effectively two orders of magnitude increased computer power over currently available resources. By the mid-1990s when the satellites are fully functioning and WOCE is in full swing, even greater needs are likely. Each of the above model configurations would require on the order of 200 megawords of memory.

Table 4 shows the estimated annual requirement for oceanography resources by activity based on a single CRAY X-MP processor.
<table>
<thead>
<tr>
<th>Projects</th>
<th>Memory in MW</th>
<th>Simulated Run Time (Years)</th>
<th>CPU Hours/ Simulated Year</th>
<th>Number Experiments/ Calendar Year</th>
<th>Total CPU Khours/ Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean GCMs</td>
<td>50</td>
<td>250</td>
<td>150</td>
<td>2</td>
<td>75</td>
</tr>
<tr>
<td>Equatorial Model</td>
<td>10</td>
<td>10</td>
<td>200</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Reg OC Models</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td>GFD</td>
<td>25</td>
<td>25</td>
<td>120</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>Coupled Models</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>Sat Obs - Data Assim</td>
<td>50</td>
<td>10</td>
<td>125</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>Total (annual hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>335</td>
</tr>
</tbody>
</table>

Table 4. Resources needed for oceanography
2.5 Turbulence Theory

(Steven Orszag, Robert Kerr, and Jackson Herring)

Fluid motions that transport heat and momentum in the atmosphere and oceans are nearly always turbulent. Thus, to progress in our understanding of important fluid dynamical processes, it is vital to improve our ability to assess how turbulence affects large-scale eddies, their trajectories, and associated transports. Turbulence is characterized by many interacting scales of motion. In practice, their sizes range over factors of thousands, with interactions between eddies of similar scales intense, and those between dissimilar scales more feeble. Generally, these interactions transfer energy from large to small scales, with considerable degradation of information as the cascade to small scales proceeds. Were these interactions without information loss, the flow would not be considered turbulent. The small scales would, in that case, be slaved to the large, and the presence of the former would be manifest simply as sharpening of the edges of the otherwise smooth large scales. If, on the other hand, the cascade were such that information between interacting scales was totally lost, the degree of chaos would not permit any appreciable coherence to be transmitted to small scales, and the small scales would assume a role analogous to "molecular" chaos. The characterization of their role in transport processes would then be much easier. The ratio of the maximum scale-size to the smallest effective scale in the flow defines the Reynolds number $R_A$. For atmospheric and oceanographic flows, $R_A$ ranges from thousands on up (with scales ranging from thousands of kilometers to centimeters). In all fluids, including air, water, and solar gases, the most important consequence of turbulence is the profound modification of transport of momentum, energy, and particles from one location to another.

The fundamental characteristic of turbulent flows that makes them so difficult is that they exhibit much more small-scale structure than their nonturbulent counterparts. The existence of small-scale structure is evidence of enhanced transport in that small scales develop from the degradation of large-scale excitations that are maintained by energy transport from one scale to another.
fundamental difficulties of turbulence are that excitations extend over a huge range of scales and that no comprehensive theoretical framework exists from which to infer the degree of correlation among these scales. In the cascade from large to small scales, the nonlinearity plays a pivotal role 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 so on the time scales of dynamical interest. The limited predictability of atmospheric motions is a consequence of the basic instability of turbulent flows. 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 "strange attractors."

It has become clear over the past decade that to make substantial progress in our understanding of turbulent flows, we must utilize 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 theories of turbulence
- Numerical tests of turbulent transport approximations for use in large-scale computer models of the atmosphere
- Numerical studies of large-scale dynamics using large-eddy simulations
- Studies of the origin of turbulence, including investigations of possible routes leading to chaos (apparent random behavior)
2.5.1 Recent History of Turbulence Computations

NCAR has played an historic role in advancing the state of the art of turbulence computations. These include:

- The first numerical simulations of two-dimensional turbulence (Lilly, 1969)
- The first numerical simulations of three-dimensions turbulence (Orszag and Patterson, 1971)
- The first large-eddy simulation of shear and convective turbulence (Deardorff, 1970)
- The first large-eddy simulation of turbulence in a stratified shear flow (Deardorff, 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. However, such new ideas are difficult to predict, in both their direction and consequences. 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. Scientific opportunities often present themselves unexpectedly; hence, the estimates given in this section should be considered conservative.

In the following paragraphs we review progress on certain key problems in turbulence-theory and application, and note the current unsolved issues that numerical simulations have raised. We start with a brief statement of the state of affairs circa 1975. We shall in addition point out, for these particular problems, how the next-generation of supercomputer (the CRAY-3 level) would, with the reservations and uncertainties noted above, yield new insights and results. We shall then be in a better position to discuss the kinds of development anticipated in the 1990s.
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In 1975, before the introduction of the early Cray machine, state-of-the-art turbulence simulations involved full numerical solutions of the Navier-Stokes equations with up to $32 \times 32 \times 32$ degrees of freedom in three spatial dimensions and $128 \times 128$ degrees of freedom in two dimensions. Low Reynolds number inertial-range dynamics were 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 developing nicely, through 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 considered all relevant scales of motions were only in their infancy, and scientists were just beginning to perceive the usefulness of such methods in providing answers to fundamental fluid dynamical questions.

Since 1987, with the installation of newer Cray computers at NCAR, studies have been performed using computer codes with several orders of magnitude more resolution than possible with the Control Data 7600. Generally, the early Crays brought into numerical scrutiny a range of stability problems in three-dimensional turbulence, and permitted the rudiments of inertial ranges to be defined, for simple geometries. For two-dimensional turbulence, considerable progress was made in incorporating inertial range effects.

Some direct numerical simulations studies which have yielded new insights are described below. Most of these problems are as yet not completely solved, but need C-90/CRAY-3-level computing before the high $R_e$ asymptotic are manifest.
2.5.2 Taylor-Green Vortex, Vortex Reconnection, and Three-dimensional Inertial-range Dynamics

There are certain simple initial value problems which have yielded significant insight into the way the non-linearities in the Navier-Stokes equation led to ever smaller scales of motion and the rapidity with which this happens. Two problems come immediately to mind, in this connection: the Taylor-Green problem, which is a regular system of vortices arrayed initially two-dimensionally; and the vortex reconnection problem, a pair of closely-spaced, well defined vortices with opposite circulation. For these two problems, mesh sizes as large as $64^3$ – on the early Cray – were accommodated on a routine basis. For the Taylor-Green problem, which takes advantage of symmetries in the initial conditions, this size allowed the equivalent of a $256^3$ mesh to be simulated. These results gave the first indication that the inertial subrange could be computed directly on existing machines. One question that these calculations could not resolve is whether there exists a singularity of the incompressible, inviscid Euler equations.

With the addition of fast secondary memory storage (SSD) on the X-MP-level machine, as well as better utilization of vector processing, meshes the order of $128^3$ points are now commonplace. At this level, some homogeneous calculations show an inertial subrange and the vortex reconnection problem shows an inertial subrange. Symmetries have allowed meshes equivalent to $1024^3$ points, without the symmetries. With this resolution, some of the finer points for turbulent dissipation, such as acoustic noise generation, have been observed and there is now good numerical evidence that the Euler equations has a weak singularity (i.e., the vorticity becomes unbounded on a set whose measure is less than the volume of the flow). If the singularity of the Euler equation is weak, in the above sense, then much of the traditional thinking about the universal nature of high Reynolds number turbulence is in question. Before we can be certain of this point, however, high resolution ($\sim 512^3$) unsymmetrical experiments must confirm that the flow inhibition imposed by symmetry is not dynamically significant.
The vortex reconnection problem elucidates many aspects of the production of small-scale turbulence, including dissipation and the production of acoustic noise. For a proper understanding of dissipation [including the analogous effect in magnetohydrodynamics (MHD) flows], it is probably a vital mechanism. Indeed, the magnetic field line reconnection process is the outstanding unresolved issue in MHD flows.

To investigate the degree to which the vortex-reconnection or other similar mechanisms participate in the inertial range dynamics, the C-90/CRAY-3 level computer will be clearly necessary. This point is brought home very forcefully by recent (wavelet) analysis of experiments at $R_\lambda \sim 1000$, which indicates a multi-fractal structure to the inertial range dynamics, that sets in only for flows for which $R_\lambda \geq 200$. This would require the equivalent of $1024^3$ points.

2.5.3 Two-dimensional and Quasi-geostrophic Flows

Two-dimensional flows are the prototype of the large scales of the atmosphere, in which the constraints of rotation and stable stratification are paramount. As noted earlier, NCAR was an early leader in investigating these dynamical issues. Calculations using improved resolution of the past ten years (up to $1024^2$) have profoundly affected our understanding of these flows. Thus, an initial state of random vorticities tends in time to become a system of isolated vortices, whose dynamics are controlled by their distant interactions, with an occasional collisional-interaction. Their scale size distribution is set by their initial distribution: the classical picture of a universal scale size distribution $E(k) \sim k^{-3}$ has a very limited validity, and that at only intermediate times. These ideas are now being confirmed in current studies quasi-geostrophic flows (fully three-dimensional, but still rapidly rotating), and it will be most important to see how much of the two-dimensional picture carries over. Undoubtedly, the next-generation machines will do for the rotating, stably stratified (i.e., turbulence with waves) flows (with various additional effects, such as topography) what the X-MP did for two-dimensional turbulence. A major question here is the extent to which the non-wave component of such turbulence is analogous – in its dynamics – to
two-dimensional turbulence. Stratified turbulence has many of the features of compressible turbulence, and will require a similar increase in computer capacity to simulate.

2.5.4 Turbulent Magnetohydrodynamics

The earlier studies of MHD at $64^3$ resolution have been extended to $128^3$, since the advent of the X-MP class computer. At present, the X-MP is able to treat high-resolution, two-dimensional ($128^2$) and moderate resolution three-dimensional flows ($64^3$) flows. For the two-dimensional case, a considerable inertial range is thus available; but for three-dimensions, inertial range effects are unresolved. Another effect brought under numerical scrutiny is the problem of magnetic-field line reconnection (in two dimensions) which is a dissipative process at extremely small scales. It is analogous to the vortex-reconnection problem, but considerably more complicated. Three-dimensional calculations here must await the next-generation machine. New directions in MHD are the study of the effects of compressibility, and the study of three-dimensional field line reconnections, for which a C-90/CRAY-3-level computer is clearly needed. These computations also have applications in fusion research, as well as the heating of the corona. In particular, we have little understanding of the non-linear regimes of these flows.

2.5.5 Large-eddy Simulations

Of great practical importance are large-eddy simulations, in which the effects of scales smaller than the grid scale on those retained in the calculation are modeled statistically. This method is in reality the only hope we have of detailed modeling of the real atmosphere, and has wide application ranging form global models to the planetary boundary layer. The current level of computations is $96^3$, with simulation of the full planetary boundary layer, including radiation and condensation. Stratus-topped planetary boundary layers may now be studied via LES simulations. Their input into global climate models will be of great significance, which appears to be the next step in their application. For this, the C-90/Cray-3 computer is clearly required. Of equal importance, is the
extension of LES to boundaries, via algorithms derived from the new methods such as the renormalization group RNG. Such procedures have the potential of eliminating much uncertainty in the present applications.

2.5.6 Convective Flows

With resolution \( (128^3) \) and resources (the order of 50 single processor X-MP hours), we have been able to simulate well-resolved homogeneous turbulence with a distinct, but short, inertial subrange. For shear flows over boundaries, an inertial subrange has been obtained by an expenditure of 1000 X-MP hours. If we assume that for wall-bounded flows, a resolution that allows both a well resolved boundary layer and an appreciable inertial range well away from the boundary is one that reveals the asymptotic \( (R_{\lambda} \to \infty) \) of the flow, then we may be at present nearing the threshold where thermal convection with many of the properties of real atmospheric convection may be studied via direct numerical simulation (DNS).

Of interest here is not only verification (or repudiation) of the traditional scaling laws (which are currently seriously contested), but also the statistics (distribution function level) of various flow quantities (such as vorticity and temperature differences). We should note that recent high-precision experiments have shown a sequence of transitions toward progressively more chaotic flows through which the flow proceeds as the basic buoyancy driving force is increased. The current level of computations is now able to adequately simulate connective systems up to a Rayleigh number \( (R_{\alpha} = \text{a non-dimensional measure of the buoyancy driving force}) \) of \( R_{\alpha} = 5 \times 10^6 \). An examination of the statistics of the flow of this value of \( R_{\alpha} \) suggests that we might have observed the transition to this Reynolds number scaling regime. Confirmation of this transition will require 80 X-MP hours. This resolution is on the verge of producing inertial range dynamics in the interior of the flow; we need the same factor of 20 increase in computer power used to see inertial effects in shear flows and to see possible asymptotic behavior of these convective flows.
2.5.7 Boundary Layers

Whereas direct calculations of turbulent convective flows are in their infancy, one area where the value of direct simulations has been clearly demonstrated is turbulent boundary layers. Numerical methods of completely resolving the instability mechanism in the boundary layers were developed in the mid-1970s and with X-MP-class machines, variations on these methods have allowed scientists to study fully turbulent boundary layers over smooth rigid surfaces at moderate Reynolds numbers. These calculations have confirmed the shedding of horseshoe vortices and turbulent streaks observed experimentally, and with the detail provided by simulations, the mechanisms that produce these structures have been identified. One calculation at NASA Ames that required 1000 X-MP hours was even able to produce a short inertial subrange [4].

An objective at NCAR is to extend these methods beyond simple shear and convection to flows with stratification, rotation, and mixtures of these effects. Simulations of stratified shear flows are only beginning, but initial calculations suggest that an order of magnitude greater computing power will be necessary to reach the same effective Reynolds numbers as sheared calculations without stratification. This implies that we can expect to see the beginnings of turbulent effects on an X-MP-class machine, but that it will require the next generation to study completely the effects of stratification in boundary layers..

Another question that requires the next-generation supercomputer is the true nature of boundary-layer structures. Existing visualizations of horseshoe vortices suggest that they are tubelike. But statistical analysis of homogeneous shears suggests that at a sufficiently high Reynolds number, the structures will be sheetlike. This is supported by the vortex reconnection calculations where vortex tubes are transformed into vortex sheets. The conclusive demonstration of vortex sheets in the reconnection problem required pushing the limitations of the X-MP, although the signs of sheet structures appeared in lower-resolution calculations. If horseshoe vortices really are vortex sheets, we expect to see the first signs of this with X-MP calculations, but the next generation of
supercomputer will be necessary to demonstrate this conclusively. The nature of the small scales of turbulence has important implications for modeling turbulent boundary processes in larger-scale codes.

2.5.8 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 C-90/Cray-3 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).

Table 5 shows the number of hours of central processor time on a single CRAY X-MP processor that will be required annually for each of the problem areas just discussed. However, it must be remembered that the CRAY X-MP is severely limited in dealing with this class of problems. Not only is the CRAY X-MP's memory too small, but also such long runs would be required on it that elaborate programming techniques would be necessary, to cope with any interruptions in the run. Until an upgrade to the CRAY X-MP 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>Subject Areas</th>
<th>CRAY X-MP K Hrs/Year</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Small-scale (inertial-range) turbulent structure calculations (two- and three-dimensional)</td>
<td>12</td>
<td>50M</td>
</tr>
<tr>
<td>2. Large-eddy and renormalization group studies</td>
<td>10</td>
<td>150M</td>
</tr>
<tr>
<td>3. Wall-bounded turbulence studies</td>
<td>8</td>
<td>50M</td>
</tr>
<tr>
<td>4. Free stratified shear flow turbulence (internal waves) studies</td>
<td>10</td>
<td>150M</td>
</tr>
<tr>
<td>5. Quasi-geostrophic and rotating turbulence</td>
<td>8</td>
<td>25M</td>
</tr>
<tr>
<td>6. MHD Turbulence and dynamos</td>
<td>4</td>
<td>150M</td>
</tr>
<tr>
<td>7. Shear flow transition studies</td>
<td>4</td>
<td>50M</td>
</tr>
<tr>
<td>8. Convection and MHD convection</td>
<td>6</td>
<td>150M</td>
</tr>
<tr>
<td>9. Analytical theories, especially inhomogeneous, anisotropic flows</td>
<td>4</td>
<td>20M</td>
</tr>
<tr>
<td>Total</td>
<td>66</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Time needed for turbulence study based on a single X-MP processor
2.6 Solar Astrophysics and Solar-terrestrial Interactions

(Compiled by V. J. Pizzo [HAO/NCAR], in consultation with R. G. Athay, P. A. Gilman, R. Roble, and E. Shoub [HAO/NCAR]; A. Pouquet [HAO/ASP/NCAR]; and with D. Mihalas [University of Illinois], R. Stein [University of Michigan], R. S. Steinolfson [University of Texas at Austin], and P. Woodward [University of Minnesota].)

2.6.1 Introduction

The supercomputing needs in solar astrophysics and solar terrestrial relations differ somewhat from those of the rest of the atmospheric community. While large, computationally-expensive models play a critical role in solar convection, radiation hydrodynamics, MHD turbulence, and ionospheric/thermospheric studies, the emphasis is generally on more moderate-sized models developed and used by one or a few scientists. Because the physical parameter space of most astrophysical systems is so poorly known, such models tend to be more limited in scope and their structure and content are subject to frequent, extensive modification. Numerous runs may be necessary to establish even the basic properties of the system with any degree of confidence.

Data reduction, too, places demands on astrophysical computing that have no parallel in terrestrial atmospherics. By definition, virtually all astrophysical data are of the remote sensing variety, where temporal, spatial, and spectral information are combined in complex ways in every datum. In many cases, the deconvolution effort required to extract meaningful physical quantities from such data presents a computational challenge on a par with some of the larger theoretical numerical models. In addition, the global nature of the radiative transfer effects in the surface layers of many astrophysical objects tends to couple the particulars of the deconvolution rather tightly to assumptions made about its atmospheric structure. Hence, progress in the determination of the true physical state of the system hinges upon a close, iterative symbiosis of exacting observations and detailed physical models.
With the X-MP, major advances have been made in many areas, including work on the solar dynamo problem; the incorporation of radiation into models of the granulation; detailed magnetostatic models of solar surface features; comprehensive treatment (in a slab geometry) of the radiative processes giving rise to the photospheric, chromospheric, and transition zone properties of the sun; and the description of the complicated thermal, chemical, radiative, magnetic, and dynamic interactions taking place in the earth's upper atmosphere.

2.6.2 Specific Research Areas

A summary of the research areas that stand to benefit greatly from the availability of a major new supercomputer upgrade are described in this section. As will be seen, the specific computational needs vary considerably, with the greatest augmentations being required by solar convection, MHD turbulence, and terrestrial thermospheric modeling.

2.6.2.1 Solar Cycle/Dynamo [Gilman, DeLuca]

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 members 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 periods. 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.

Building upon progress made in the 1970s with relatively simple, linear dynamo models, the full magnetohydrodynamic dynamo and differential rotation problem was attacked systematically in the early 1980s. This effort was carried out 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. In particular, calculations for a convectively driven dynamo incorporating the observed surface differential rotation have the toroidal fields migrating toward the poles with time, rather than toward the equator as seen on the sun.

It appears that the primary reason for the migration of toroidal fields toward the poles in the model is that the differential rotation driven by the convection decreases with depth, being approximately constant on cylinders concentric with the axis of rotation. Now, helioseismological studies using solar acoustic modes are telling us that the angular velocity does not vary significantly within the convection zone, at least at low and mid-latitudes where sunspots are found. The observations also suggest that the rotation rate of the solar interior lying below the convection zone is nearly independent of latitude, with a value intermediate between the maximum and minimum surface values. These results imply there should be a rather large radial gradient of angular velocity across the interface between the convection zone and interior. This result, taken together with other arguments, points to the "seat" of the solar dynamo being in the interface layer, rather than in the bulk of the convection zone above.

Dynamo modeling efforts are now beginning to focus on this interface layer. Early models are relatively simple and require only modest supercomputing resources. However, supercomputing requirements are expected to grow substantially because a number of fluid dynamical and magnetohydrodynamical processes need to be modeled in detail. These would include those.
properties of the fluid motion of particular importance for determining dynamo action, such as helicity and turbulent transport, as well as the mechanism leading to the break-up of large toroidal magnetic flux rings into smaller magnetically buoyant elements that rise up into the convection zone. In addition, 3-D numerical simulations will be needed to establish what happens to the magnetic flux once it gets into the convection zone; what we see at the surface has been "processed" by convection and differential rotation in the convection zone overlying the interface layer.

2.6.2.2 Small-scale Solar Convection [Stein]

Currently, simulations of solar convection include both magnetic fields and local thermodynamic equilibrium (LTE) 3-D radiative transfer. However, major deficiencies remain in the physical description due to the low resolution and corresponding high viscosity in the simulation, the small range of length scales that can be simulated, the inability to include much of the chromosphere due to restrictions of the Courant time step, and the non-LTE nature of the radiation. All this leads to very lengthy computations (hundreds of hours of CPU time on an X-MP-class machine) to complete a single simulation (several hours of solar time).

It would be very desirable to increase the number of computational grid points to increase both the resolution and the range of length scales. This would require more memory, faster disk input/output (I/O), and faster CPUs. The resolution-viscosity problem could be alleviated somewhat by using higher order algorithms (e.g., PPM), but these tend to be very difficult to use for 3-D MHD. A 3-D adaptive mesh would also improve the calculation, and will undoubtedly be implemented at some time in the future. However, memory size and speed will always be bottlenecks. The problem of small Courant times is unavoidable in an explicit code, and an implicit code would be even more time consuming. Non-LTE transfer algorithms are currently being developed for 3-D, but these would add an enormous amount of time to the calculation. However,
it may be possible to partially circumvent this latter problem by clever parameterization in those cases where only the gross energy balance is of interest.

Hence, a faster machine with more memory would allow us to include a wider range of scales, from granulation to super-granulation at a higher resolution, to better approximate the large Reynolds number turbulent situation that exists on the sun.

2.6.2.3 Fluxtubes and Sunspots [Pizzo]

Magnetic flux is thought to be generated deep in the solar convection zone in the form of filamentary strands that are loosely bundled together into discrete structures known as fluxropes. Eventually, magnetic buoyancy causes segments of a fluxrope to break free from their moorings and float to the surface, where the flux emerges in a characteristic bipolar pattern. In the photosphere, the nearly vertical magnetic structure may be constricted and the field intensity amplified by a combination of radiative and dynamic processes. Although such flux concentrations occupy less than one percent of the solar surface at photospheric levels, they spread rapidly with height by virtue of the magnetic pressure they exert on the surrounding field-free region. Thus, just a few thousand kilometers up in the chromosphere, magnetic flux permeates the entire solar atmosphere.

The balance of forces and energy transport in magnetic concentrations at the solar surface depends critically on their spatial scale. The smallest structures consist of one or a few magnetic strands, and are known as fluxtubes or magnetic elements. Because they fall below the current limits of observational resolution, their properties are poorly known. However, indirect evidence suggests they have diameters of 200 km or less and field strengths of the order of 1,500 Gauss in the photosphere. Due to their small size, radiation from the surrounding hot material in deeper layers is able to stream freely up and heat their interiors in the visible layers. Hence, when viewed from above, fluxtubes should appear as tiny bright dots (or rings) on the solar disk.
More extensive aggregations of magnetic strands occasionally come together and persist, by means not yet well understood, as pores and sunspots. These features are so large (up to 40,000 km across) that radiation cannot effectively penetrate laterally into their interiors. Since they also apparently inhibit the convective energy transport from the deeper layers, they are therefore nearly 2,000 degrees cooler than the quiet photosphere and thus appear dark against the solar surface. Although their large scale size makes them most conducive to observation, and despite the close scrutiny to which they have been subjected over the years, only the gross aspects of their equilibrium structure are known with any confidence.

Progress in understanding the physics of flux concentrations has up to now been thwarted by the lack of of hard, quantitative observational information and the rather primitive state of the theoretical models. In the next decade, however, the observational situation promises to improve dramatically as a new generation of instruments, both ground-based and orbiting, begins to return measurements of the thermodynamic and vector magnetic properties of these structures with high spatial and spectral resolution. It is anticipated that individual fluxtubes will become visible to us for the first time, and that important aspects of the structure of pores, umbral cores, and the penumbra will at last be susceptible to meaningful scientific investigation.

With X-MP-class machines, it is now just feasible to generate 2-D axisymmetric models of fluxtubes and sunspots with sufficient resolution to provide adequate self-consistent treatment of the mechanical force balance and the continuum radiative equilibrium in the grey atmosphere approximation. At reduced resolution, some of the dynamic effects thought to be relevant to fluxtube physics can also be included. For example, extant models suggest that downflows in the unmagnetized region about fluxtubes may make important contributions to the photometric signature and may have observable impact upon the convection patterns in their immediate vicinity. However, the physical scale of these motions is affected by the limited size of the computational domain and the granular convection is only crudely modeled.

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An advanced supercomputer is required for the construction of models incorporating the relevant magnetohydrostatic and dynamic processes over a domain large enough to obviate the troublesome boundary effects and to permit proper treatment of the high-gradient regions associated with the thin current sheets forming the walls of these structures. Wavelength-dependent, line, and Non-local Thermodynamic Equilibrium (NLTE) processes could also be added to the radiative transfer description to improve upon the energetics. In related applications, the role of radiation in establishing the penumbral properties could be tackled using much the same mathematical machinery, and the origin of the Evershed flows could also be pursued.

In recent years, much progress has been made in the analytic treatment of 3-D magnetostatic structures. While these studies utilize certain assumptions for tractability and represent gross idealizations of the real physical phenomena in conjunction with the detailed axisymmetric models described above, they have nevertheless paved the way for more realistic 3-D numerical models that could be run on an advanced supercomputer. Even with simplifying parameterizations, 3-D magnetostatic models of sunspot groups would constitute a major advance, as the large-scale magnetic connectivity and asymmetries could be addressed for the first time. Such models are certain to be computationally demanding, especially if radiative processes are reasonably included. The diagnostics necessary for the fruitful analysis of these simulations would constitute a major commitment of computing resources.

2.6.2.4 Radiation Hydrodynamics [Mihalas and Athay]

The solar atmosphere is maintained at temperatures much in excess of the radiative equilibrium temperatures by a source (or sources) of mechanical energy input of uncertain origin. The mechanical heating is accompanied by momentum input giving rise to large amplitude fluid motions. One of the current goals of solar research at NCAR is to construct models of the solar atmosphere with prescribed levels of heating. By matching such a model to the best empirical
model, we are learning much about the nature of the mechanical energy input. In particular, the magnitude of the required mechanical energy flux and its rates of dissipation will provide both boundary conditions on the heating mechanism and clues to the identity of the physical processes involved in the heating.

The construction of reliable models with mechanical heating faces a number of challenges. Thus far, the models have been quasi-hydrostatic. Motions are included only as small-scale random turbulence added to the thermal velocity. It is necessary to include such motions to broaden spectral lines above their thermal width, and, correspondingly, to increase the pressure scale height.

To properly model a stellar atmosphere, it is necessary to include all of the essential sources of opacity. The opacities are important in two separate aspects. On the one hand, the opacity determines the spectral distribution of the radiation flowing through the atmosphere. Neglected opacities allow too much energy to flow through at a particular wavelength, which, in turn, modifies the temperature structure. If the missing opacity is in the ultraviolet, the excess radiation ionizes some of the more abundant metals leading to an incorrect electron density. On the other hand, particular sources of opacity are also the primary sources of the excess radiation that balances the mechanical heating, and it is critical to identify and include all significant sources.

In the mechanically heated parts of the solar atmosphere, the main sources of opacity are in spectral lines of molecules, neutral atoms, and ions. Individually, there are some $10^7$ spectral lines that need to be included. Practical considerations imposed by computer speed and storage limit the number of frequencies that can be handled to a few thousand, which requires that most of the lines be treated statistically.

The radiation that balances the mechanical heating arises primarily from inelastic collisions between free and bound electrons (atomic and ionic lines) and between collisions of atoms and molecules.
(molecular vibration-rotation bands). The latter is important only near the lowest temperatures in the solar atmosphere, and it is mainly the electron-ion collisions that provide the radiation loss through the bulk of the atmosphere.

The problem of determining the energy balance between mechanical heating and radiation can be expressed in terms of electron distribution functions, including the relative proportions of free and bound electrons, and the distribution of the bound electrons among the various atomic and ionic energy levels. The heated portion of the solar atmosphere is not in thermodynamic equilibrium and, in the chromosphere, the electron populations are not functions of temperature only. Instead, the photon distribution plays an important role. This requires that the electron distributions be determined self-consistently with both the photon distribution and temperature.

Current modeling efforts are limited by the capacity and availability of X-MP-class computers. In addition to the need for several thousand frequency divisions, we need large numbers of depth divisions (covering up to 8 orders of magnitude in density) and several angular divisions. These demands, coupled with the large number of bound atomic and ionic energy levels that must be treated, compromise current models. We need more complete models, as well as more variety of models with differing amounts of heating and extending through greater ranges of depth. In addition, we will eventually need to include hydrodynamic effects. Progress on these extensions will be limited until a new generation of computers is available.

2.6.2.5 MHD Wave Theory

- Slow, Intermediate, and Fast Phenomena on the Large Scale [Steinolfson]

The existence of a magnetic field in a plasma may have a significant influence on the propagation of disturbances through the plasma. The addition of magnetic forces and the storage of energy in the magnetic field produce phenomena that are entirely absent from a
much simpler fluid system. The qualitative difference between fluid and MHD systems is best known for the important case of linear waves, where the magnetic field introduces new wave modes that are not present in a nonmagnetic fluid. The typical features and characteristic speeds of MHD modes depend on the direction of wave propagation with respect to the magnetic field. There are three linear modes (slow, intermediate, and fast waves) in MHD, and only one (sound wave) in an ordinary fluid. When the waves become nonlinear and when shock waves are formed, there are similarly three MHD modes, analogous to the linear waves, and one fluid mode.

The only places where these modes can be studied experimentally at astrophysical scales is in the solar corona and the earth's magnetosphere. White-light coronagraphs observe large-scale density variations in the corona that often occur as a result of an initiating mechanism near the solar surface. These transient events are referred to as coronal mass ejections (CMEs). Earth-orbiting satellites provide in situ measurements of, for instance, the earth's bow shock and shocks associated with reconnection in the magnetotail. The CME observations have the advantage that the entire phenomena is observed rather than just one point, as for the satellite measurements. Although CMEs have been studied extensively for more than fifteen years, they are just one example of numerous astrophysical phenomena that are believed to involve an impulsive ejection of material with the possible formation of MHD shocks. Other examples include the energy release in active galactic nuclei, star formation by supernova explosions, and astrophysical jets. In addition, the optical signal observed near stars may be produced by slow wave phenomena. The study of MHD wave modes in CMEs, then, provides results that have a much broader application.

Numerical simulations are essential for the interpretation of CME observations, since the only quantity observed in CMEs is the density change. CMEs often originate near the base of coronal streamers and subsequently propagate outward through the streamer. Such a
streamer is used as the initial state for the computations. However, due to present limitations on the number of grid points that can be used in this two-dimensional simulation, the resolution in the streamer current sheets is so poor that much of the most important part of the evolution becomes obscured. An improved numerical description of the mode interaction, such as front-tracking methods, may also be necessary. Both enhancements are inherently expensive computationally and require the use of an advanced supercomputer.

- Waves in Flaring Magnetic Geometries [Pizzo]

With an advanced supercomputer, one could contemplate modeling wave processes occurring within the confines of rapidly flaring magnetic structures like sunspots and the upper-photospheric layers of fluxtubes. This question is extremely important for the understanding of the heating of the chromosphere, for the interpretation of spectral information from small-scale magnetic features, and for the scattering and dissipation of wave energy about sunspots. In addition, wave motions guided by the sharply bending fieldlines at the edges of sunspots may be related to the Evershed flows observed to propagate radially outwards from large spots. Up to now, studies of nonlinear wave evolution in surface magnetic concentrations have been largely limited to 1-D geometries, while only exploratory work on small-amplitude 2-D propagation has been accomplished. While considerable work remains to establish the proper conceptual framework for nonlinear multidimensional MHD wave evolution, such efforts will soon require the availability of an advanced supercomputer.

2.6.2.6 Solar Plasma Physics [Shoub]

- Plasma Physics in the Lower Solar Transition Region
For the empirically-minded solar physicist, the lower transition region \((2 \times 10^4 K < T < 2 \times 10^5 K)\) is perhaps the least well understood region of the outer solar atmosphere because its temperature/density structure, as deduced from Extreme Ultra-violet (EUV) line observations, defies theoretical explanation. That is, despite numerous attempts, solar physicists have been unable to construct a theoretical model of this region which satisfies mass, energy, and momentum conservation and which reproduces the EUV emission line data.

The low transition region is also interesting from a plasma physicist’s point of view because the enormously steep temperature and density gradients \((\sim 10^{5^0} K/Mm)\) in the region give rise to significant nonequilibrium effects in the particle velocity distribution functions. In particular, the electron velocity distribution function develops a strongly anisotropic high energy tail due to the free streaming of hot electrons down the temperature gradient.

This effect has two important implications for our understanding of transition region structure. First, the classical Spitzer expression for the heat flux becomes invalid because the energy flux depends on the global temperature and density structure of the overlying corona. This implies that nonclassical thermal conduction may be a viable energy source for heating the lower transition region because enormous temperature gradients are not required to carry the energy flux to lower temperature regions, as in the classical case. Second, the high energy electrons enhance ionization rates in the transition region, so that spectral lines thought to be formed near \(10^5 K\) are actually formed at much lower temperatures. Thus, the usual spectroscopic diagnostic procedures used to deduce transition region structure from observed EUV line intensities have led to the erroneous conclusion that there is a substantial amount of material at temperatures between \(3 \times 10^4 K\) and \(2 \times 10^5 K\).
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Theoretical investigation of these issues requires numerical solution of the Fokker-Planck equation (a nonlinear three-dimensional integro-differential equation, in the present context) and the self-consistent calculation of trace element ionization equilibrium and radiative losses. All of these tasks are computationally intensive.

- Acceleration of the Solar Wind

A longstanding and serious gap in our understanding of the solar wind is our inability to identify the means by which high-speed streams are accelerated to speeds of 500 to 800 km/second at the orbit of the earth. Theoretical studies of the solar wind expansion have traditionally relied on one of two dramatically opposed assumptions; namely, that the wind is collision-dominated, or that it is collisionless. Until quite recently, it was thought that models based on the assumption that the plasma is collision-dominated should be valid out to heliocentric distances of 10-20\(r_\odot\), for it is only beyond this point that the collisional mean free path exceeds gradient scale lengths. Since the flow has reached its terminal speed at these distances, breakdown of the collision-dominated approximation at larger radii was not considered a serious flaw. (Collisionless models appear to be more appropriate in the region beyond 20\(r_\odot\).) Nevertheless, collisional thermal models (i.e., no energy source for the wind other than thermal conduction and convection across the base) that satisfy reasonable boundary conditions on temperature and pressure at the sun predict flow speeds at 1 AU which are substantially less than are observed.

The inability of thermally driven, collision-dominated hydrodynamic models to explain the observed properties of high-speed streams may stem from their failure to account for hydromagnetic waves postulated to propagate across the coronal base. However, there is little observational evidence to support (or negate) this conjecture, and detailed self-consistent models incorporating this effect have not yet been constructed.
Recently, it has been recognized that for the results of collision-dominated transport theory to be valid, it is necessary that the mean free path of all particles that contribute substantially to each important process be less than the relevant gradient scale lengths. Unfortunately, this condition is violated almost everywhere above the coronal base. We are thus in a position of being unable to specify the heat flux, which is perhaps the dominant energy source for thermally driven wind models. Indeed, preliminary calculations based on kinetic theory suggest that this is so; if true, it means that thermally driven models have failed simply because we have not modeled the physics accurately.

Unfortunately, a meaningful description of this effect requires a full kinetic treatment of the electrons. Moreover, the classical treatment of viscosity (i.e., of momentum transport by thermal motions) likewise fails in the near-sun region, so that the protons should also be treated by kinetic theory.

If the usual London collision operator is used to model Coulomb interactions and if the electron and proton velocity distribution functions are assumed to be isotropic in the plane perpendicular to the local magnetic field, the computational problem reduces to the solution of a boundary value problem for a pair of coupled, nonlinear integro-differential equations in three independent variables (two velocity-space variables plus radial location). The equations are parabolic in nature (with the radial coordinate playing the role of the time variable), so that the 3-D problem can be treated iteratively by marching backward and forward in radius. Numerical stability limitations require that the spatial differencing be implicit, so that a large 2-D matrix must be inverted at each depth step. Moreover, due to the nature of the collision terms, the resulting matrix equations are strongly ill-conditioned and must be solved directly rather than iteratively. The nonlinearity in the equations is treated iteratively. For a mesh of 500 velocity points, 100 angles, and 1,000 radial points, the computation problem reduces to the solution of a sequence of block tridiagonal matrix equations of order \( N = 2.5 \times 10^4 \) (i.e., \( N = \# \) of unknowns per depth). Such equations
must be solved at each of 1,000 depths, in both directions (backward and forward radial integrations are coupled due to angular scattering terms) for a total of roughly 25 iterations (five iterations per coefficient evaluation). This is to be done for each of two equations. Thus, $1,000 \times 2 \times 25 \times 2 = 10^5$ matrix equations of order $N = 2.5 \times 10^4$ must be solved per run. Using optimized assembly language routines to do the linear algebra and the SSD for intermediate storage, approximately three hours of CPU time are required on the CRAY X-MP. Additional intermediate calculations plus graphical output add approximately 1 CPU hour per run for a total of 4 CPU hours per run. The problem is thus computationally intensive.

- Solar Wind Microphysics

The velocity distribution functions calculated as described above evolve radially under the joint influence of collisionless streaming and Coulomb interactions. Because the latter become increasingly weak as the density decreases, the distributions become increasing non-Maxwellian with increasing radius. At some location (probably not far from the sun, say 2-5 $\text{R}_\odot$), one or more microinstabilities are triggered, and wave-particle interactions thereafter play a role in driving the distributions toward the local Maxwellians observed in interplanetary space. To model the effects of wave particle interactions, three ingredients are needed: a) a method for analyzing the calculated distributions for stability, so that we can identify which mode first goes unstable and the radial location where it does so. The stability analysis should allow for off-axis propagation of both electrostatic and electromagnetic modes; b) a determination of how the unstable mode saturates, so that a model wave-particle interaction term may be formulated. Mode saturation can be studied using 3-D particle-in-cell simulations; c) using the knowledge gained in step (b), a wave kinetic equation and wave-particle interaction terms to be included in the particle kinetic equations can be formulated. These kinetic equations can then be integrated as in part (a) until a new instability arises, at which point steps (b) and (c) are repeated. In this way, we
hope to "boot strap" our way outward from the sun. Each stage in this process is computationally expensive and the entire project would benefit enormously from the availability of an advanced supercomputer.

2.6.2.7 Solar-terrestrial Interactions [Roble]

The earth's thermosphere and ionosphere are controlled by the highly variable components of the sun's output. Solar energy reaches the earth mainly as electromagnetic radiation and in the form of solar wind, a flow of charged particles (plasma) from the sun. Most of the solar electromagnetic energy is in the visible region of the spectrum; it passes directly through the tenuous upper atmosphere and is either absorbed at the ground or reflected back to space. The solar electromagnetic energy at wavelengths shorter than 200 nm, however, strongly interacts with the gases in the earth's thermosphere to establish its basic chemical, thermal, and dynamic structure. Large amounts of solar wind energy are also deposited in the high-latitude thermosphere through auroral processes, sometimes locally exceeding the absorbed solar electromagnetic energy. This makes the thermosphere a dynamically active region with large variations in its global mean state caused by the variations in both the solar ultraviolet radiation output and solar wind plasma.

Satellites orbiting in the upper thermosphere experience a drag that eventually bring them down to burn up in the lower atmosphere. Since man's activities in space are increasing, there is an important need to develop large numerical models that describe the basic structure of the thermosphere and its response to solar and auroral variability.

Embedded within the thermosphere is the ionosphere, a weakly ionized plasma. The charged particles that comprise the ionosphere are strongly influenced by electric and magnetic fields. These fields, in turn, are affected by the distributions and motions of the charged particles. Mutual neutral gas/plasma interactions affect the overall structure of both the ionosphere and the thermosphere. Thus, there is a need for models of the thermosphere/ionosphere system that treat
not only the neutral gas structure and motion but also the plasma structure and motion. Of practical importance are the ionosphere's influence on radio waves and the capability of ionospheric electric currents to produce magnetic disturbances on the ground.

- TGCM

Thermospheric General Circulation Models (TGCM's) have been developed to obtain an overall understanding of the basic structure of this region of the atmosphere and its response to solar and auroral variability. For example, the NCAR TGCM solves the primitive equations of dynamic meteorology but adapted to the physics appropriate to thermospheric heights. The model solves for neutral thermospheric temperature, composition, and dynamics on a $5^\circ \times 5^\circ$ latitude-longitude grid with 25 constant pressure surfaces in the vertical. The model runs with 2.5-minute time steps and takes one hour of CRAY X-MP/48 time to simulate a single day. Typically, five days of integration time are needed to obtain a steady, diurnally reproducing state. This TGCM has been used by nearly 100 university scientists, students, and government and foreign colleagues for studies of thermosphere dynamics that involve various ground-based and satellite measurements. The TGCM is an integral part of the NSF Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program and figures in other NASA and various international programs.

- TIGCM

The NCAR TGCM is an evolutionary model and it has recently been extended to an interacting ionosphere and a self-consistent aeronomical scheme that gives a much better description of the coupled thermosphere/ionosphere system than the older version of the model. This new Thermosphere/Ionosphere General Circulation Model (TIGCM) now calculates global distributions of neutral gas temperature, zonal, meridional and vertical
winds, height of the constant pressure surfaces and number densities of the major neutral species O, O₂, and N₂ and minor neutral species H₂, A, NO(4), N(2), and NO. In addition the model calculates global distributions of the ionospheric electron and ion temperatures, electron density and number densities of O+, O₂+, NO+, N⁺, and N₂⁺ ions.

This new model operates on the same grid as the previous TGCM but runs at a five-minute time step. It currently requires 30 minutes of CRAY X-MP/48 time to simulate one day. This new model is in great demand by the scientific community, especially for lengthy time-dependent runs.

- TIGCM Extensions

There are a number of other physical, chemical, and electrodynamic processes that need to be included within the TIGCM:

a. Coupled Electrodynamic Feedback---A global dynamo model is currently being included in the TIGCM to improve couplings of thermosphere/ionosphere interactions. This extension will probably increase our TIGCM computing time requirements by 50%.

b. Extension of the lower boundary into the mesosphere---To obtain a better description of lower thermosphere/mesosphere interactions and to determine the extent of downward penetration of solar variability, it is necessary to extend the lower boundary of the model downward to about 50 km. This extension requires the inclusion of a number of different mesospheric physical, chemical, and radiative processes, and will probably increase our TIGCM computing time requirements another 50%. It will, in addition, require longer integration times, on the order of 20 to 40 days.
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c. Couplings with the Magnetosphere and Solar/Wind---Currently the TIGCM specifies these interactions empirically and there is an important need to improve the physical plasma couplings between the ionosphere and the solar wind and magnetosphere. These extensions may involve considerable computer time to adequately describe plasma transport processes. It is estimated that such interactions may require an additional 50% in computer time.

- Other Projects

There are a number of other models developed by the university community that require a next-generation supercomputer. To name a few, these include the Lagrangian ionospheric model and polar wind models developed at Utah State University and global magnetospheric models such as those developed by Rice University and at UCLA. These models will undoubtedly grow as new physical and dynamical processes are added to achieve a better description of the complex plasma physics operating in these regions of the earth's near space environment.

2.6.2.8 Observational Data Reduction and Analysis

- GONG/SOHO-SOI [Brown]

Computing requirements for scientific programs involving solar and stellar oscillations are large, and are likely to increase dramatically in the next five years due to HAO involvement in the Global Oscillations Network Group (GONG) and Solar Orbiting Heliospheric Observatory/Solar Oscillations Instrument (SOHO/SOI) projects. Tasks that will require major resources fall into three categories: image processing and low level data analysis; inversions of data to constrain physical models; and Monte Carlo simulations to yield confidence limits on statistically-derived results.

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Datasets for oscillations work typically consist of $10^4$ digital images, each containing $10^5$ to $10^6$ pixels, and each requiring extensive analysis before it is useful for scientific purposes. Typically, full disk images of the sun must be corrected for a variety of instrumental and astronomical effects, and then the entire 3-dimensional dataset must be Legendre transformed in one spatial dimension and Fourier transformed in the other spatial dimension and in time. A few thousand arithmetic operations must be performed on each pixel, and the computational efficiency hinges upon the availability of fast, random access memory of the order of several hundred megawords. Other kinds of datasets (images of parts of the solar surface, echelle spectra of stars, or direct images of star fields for stellar photometry) are of similar size, requiring similar amounts of analysis before interpretation can even begin. In the past, we have dealt with three or four such datasets per year, but with the advent of GONG, SOHO, and intensive worldwide stellar oscillations observations, we can expect this number to increase by a factor of ten in the next five years.

Inversions of oscillations data range from rather simple least-squares fits to much more complicated techniques, sometimes involving nonlinear optimization in many dimensions. Even the linear methods become difficult when one attempts to deal with all of the data simultaneously. This sort of problem (for example, determining the solar angular velocity as a function of depth and latitude) often leads to situations where one must invert matrices that are as large as feasible, given the available computing resources. Other problems, such as acoustic tomography of solar active regions, are best posed in terms of very large ($10^6 \times 10^6$) but extremely sparse matrices. Both of these applications require high levels of memory, computing speed, and precision. Other kinds of inversions involve nonlinear optimization methods such as simulated annealing, which place small demands on precision, but are extremely computation and memory intensive. Such projects are best suited for large, highly parallel architectures.
Once results are available from the reduction and inversion of solar or stellar data, it is important to supply meaningful error estimates. Because of the complicated and nonlinear character of the analysis, the only way to do this is often by way of a Monte Carlo simulation. For example, one may want to add various amounts of noise to simulated stellar oscillations data, and then pass the results through the (mildly nonlinear) reduction procedures to establish detectability thresholds. It is usually (but not always) possible to start the Monte Carlo simulation at a comparatively late stage in the analysis, bypassing most of the computation for each realization of the noise processes. The computational load therefore arises not so much from the cost of a single realization, but from the need to do a multiplicity of realizations. Both computation time and data management become onerous in such circumstances.

2.6.3 Estimate of Resources Required for Major Problems

The following table summarizes computing requirements for the largest of the problem areas discussed above: (CPU in units of single-processor X-MP)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Memory Size</th>
<th>CPU hrs/run</th>
<th>Total # Runs</th>
<th>CPU hrs/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convection (typical)</td>
<td>25M</td>
<td>300</td>
<td>many</td>
<td></td>
</tr>
<tr>
<td>256M</td>
<td>3000</td>
<td></td>
<td>few</td>
<td>10000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15000</td>
</tr>
<tr>
<td>MHD turbulence</td>
<td>256M</td>
<td>?</td>
<td>many</td>
<td></td>
</tr>
<tr>
<td>TIGCM</td>
<td>5-10 M</td>
<td>20-80</td>
<td>50</td>
<td>1900-3800</td>
</tr>
</tbody>
</table>

*Table 6. Solar astrophysics and related computing requirements*

Additional resources will be required by scientists working in other solar and interplanetary research areas.
2.7 Recent Numerical Weather Prediction Progress

(T.N. Krishnamurti)

2.7.1 Life Cycle of a Supertyphoon

One of the highlights of recent supercomputing was a real data numerical weather prediction experiment on the life cycle of a supertyphoon. This prediction, carried out by Professor T.N. Krishnamurti’s group at Florida State University, was based on six-day forecasts from a very high-resolution global model. This model successfully simulated features such as:

- The formation of a typhoon starting from a tropical depression showing a close correspondence to the observations at day three of forecast
- The supertyphoon winds in the storm on day five approached 60 ms\(^{-1}\); these were simulated very closely by the high-resolution model
- The landfall prediction at 5.6 days that was in very close agreement with observations
- The track of the supertyphoon during the first 5.7 days that had errors less than 350 km

The aforementioned results were obtained from a 170 wave (triangular truncation) global model that is about twice the horizontal resolution of current operational models. Experiments were also run at several other resolutions. Figure 4 illustrates (1) the “best fit” observed track; (2) a track based on the T170 version of the global model; (3) a track based on the T21 version of the global model; and (4) a track based on a vertically integrated shallow-water equations model at a resolution of T170.
Figure 4. Comparison between observed and computed tracks of a supertyphoon
The best results on the medium range were obtained from the multilevel global model run at a resolution of T170 that includes a comprehensive physical parameterization of the boundary layer, convective and radiative processes, and steep mountains. Apparently, the physical processes are quite important for the medium-range predictions since the purely dynamical model (the shallow-water model) performs rather poorly beyond two days, although it was also integrated at an equally high resolution, of T170.

The following table provides some of the features of the FSU global spectral model at the various resolutions:

<table>
<thead>
<tr>
<th>Wave Resolution</th>
<th>Transform Grid</th>
<th>Semi-Implicit Time Step Coefficients</th>
<th>Number of Spectral</th>
<th>Memory Required</th>
<th>Computation Time for 24 hour Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>T21</td>
<td>64 * 32</td>
<td>45 min</td>
<td>253</td>
<td>0.3 x 10^6</td>
<td>3 min</td>
</tr>
<tr>
<td>T31</td>
<td>96 * 48</td>
<td>30 min</td>
<td>528</td>
<td>0.4 x 10^6</td>
<td>4 min</td>
</tr>
<tr>
<td>T42</td>
<td>128 * 64</td>
<td>20 min</td>
<td>946</td>
<td>0.5 x 10^6</td>
<td>10 min</td>
</tr>
<tr>
<td>T63</td>
<td>192 * 96</td>
<td>15 min</td>
<td>2080</td>
<td>0.75 x 10^6</td>
<td>30 min</td>
</tr>
<tr>
<td>T106</td>
<td>384 * 160</td>
<td>10 min</td>
<td>5778</td>
<td>2.1 x 10^6</td>
<td>110 min</td>
</tr>
<tr>
<td>T170</td>
<td>512 * 256</td>
<td>6 min</td>
<td>14706</td>
<td>3.0 x 10^6</td>
<td>360 min</td>
</tr>
</tbody>
</table>

*Table 7. Features of the Florida State University global spectral model*

It is apparent that the use of a single processor makes the aforementioned computations somewhat prohibitive. A single experiment (a one-day prediction run) with a fully vectorized code using all four processors would reduce the above figures by a factor of three. To carry out a large number of medium-range (e.g., ten-day prediction runs), the demands on a CRAY X-MP/48 from a single user group would be quite prohibitive. For studies of this type to have an impact on future operational forecasting, increases in speed and memory by a factor of ten would be minimally required.
With these pioneering computations, a new thrust on the need for very high-resolution tropical (and global) modelling has been demonstrated.

2.7.2 Prediction of Atmospheric Variability on Monthly Time Scales

(By Akira Kasahara)

A real challenge exists in numerically predicting atmospheric variability on intermediate or monthly time scales. With supercomputers capable of 10 gigaflops (Gflops) and with an increasing understanding of atmospheric phenomena related to global scales, it is possible to develop the dynamical basis for monthly prediction by investigating three interrelated problems: (1) low frequency predictability; (2) stochastic-dynamic prediction strategies; and (3) systematic forecasting errors associated with model climate drift.

A next-generation computer will allow 30-day forecast experiments to be run on higher-resolution versions of a coupled ocean-atmosphere model. Execution of stochastic-dynamic prediction with a comprehensive global model needs a supercomputer one to two orders of magnitude faster than the CRAY X-MP. The reduction of systematic errors caused by a model's tendency to reach an equilibrium state different from the real climatology (climate drift) is the most immediate problem in extended range forecasting. It is necessary to build a case database of many initial states with forecasts of several months' duration. Also, to investigate hypotheses regarding the causes of climate drift, it will be necessary to perform many forecasts from these starting times. This will be an on-going project.

As it is well known, in the mid-1940s, John von Neumann of the Institute for Advanced Study, Princeton, New Jersey, embarked upon research on the problem of numerical weather prediction as the most complex physical problem yet conceived and whose solution would require the fastest
computing devices for many years to come. In describing his strategy in approaching the problem of weather prediction, von Neumann (1955) said,

"The approach is to try first short-range forecasts, then long-range forecasts of those properties of the circulation that can perpetuate themselves over arbitrarily long periods of time [such as climate simulations], and only finally to attempt to forecast for medium-long time periods which are too long to treat by simply hydrodynamic theory and too short to treat by the general principles of equilibrium theory."[5]

In terms of the present day terminology, von Neumann's short-range forecast refers to short-to-medium-range predictions which are significantly influenced by their initial conditions. Recent improvements in medium-range prediction up to ten days have appeared as the culmination of many efforts to observe the state of the global atmosphere initiated by the First Global Atmospheric Research Program (GARP) Global Experiment (FGGE).

In parallel with the advance in atmospheric modeling and in the engineering of electronic computers, steady progress has also been made in what von Neumann called "long-range forecasts," or climate simulations reproducing the annual march of an average state of the atmosphere. Climate simulations are contrasted with short-to-medium-range forecasts in that the physical parameters of the earth's system (such as the earth's radius and gravity, the constituents of the earth's system, and the solar irradiance) play significant roles instead of initial conditions. One interesting application in this category is the study of paleoclimate. We have achieved a great deal of progress in these two categories. However, as von Neumann pointed out, a real challenge exists in predicting atmospheric variability on an intermediate time scale. Achievement of this goal may be referred to as von Neumann's "dream," in contrast to the well known "dream" of L. F. Richardson (1922) who has set the course of modern weather forecasting based on hydrodynamical principles.
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We feel that the time is ripe to take on the challenge of von Neumann's dream - numerical prediction of atmospheric variability in monthly time scales. On one hand, we can foresee the availability of supercomputers with speed on the order of 10 GFLOPS. On the other hand, we begin to understand various atmospheric phenomena related to global scale, low frequency variations occurring on a monthly time scale. These phenomena include the Southern Oscillation, atmospheric responses to warm sea surface temperature (SST) anomalies in the equatorial Pacific (El Niño), the 40- to 50-day oscillations, teleconnection patterns, long-lived weather regimes (e.g., cut-off lows, blocking, and 26-day oscillations), planetary waves, and index cycle variations. These are currently among the most actively studied areas in large-scale dynamics of the atmosphere, both from observational and theoretical standpoints.

We intend to develop the dynamical basis for extended-range (30 days and beyond) prediction by investigating three interrelated problems: (1) low-frequency predictability; (2) stochastic-dynamic prediction strategies, and (3) systematic forecasting errors associated with model climate drift.

2.7.3 Low-frequency Predictability

Recent studies of atmospheric predictability indicate that the "spread" of deterministic predictions originating from an ensemble of slightly different initial conditions becomes comparable to the variance of climatology by about 12 days. However, the existence of such an average deterministic predictability limit does not imply that models are incapable of longer-range predictions of the mean state of the atmosphere averaged with respect to time, space and/or ensemble. Recent studies indicate that some low-frequency fluctuations, such as 10, 20, or 30 days time mean are predictable considerably beyond the deterministic predictability time limit. Moreover, observational studies indicate that prominent low-frequency fluctuations in time scales of days to months are found in the atmosphere as mentioned earlier.
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So far, the predictability experiments were carried out by using low resolution models such as an R15 version of the NCAR Community Climate Model. The R15 signifies the spherical harmonic expansion with rhomboidal truncation at zonal wavenumber 15. After the installation of the CRAY X-MP/48 at NCAR, we started to use a T42 version of the CCM. The following table shows the number of grid points on each horizontal level for different resolution versions.

<table>
<thead>
<tr>
<th>Version</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>R15</td>
<td>40</td>
<td>x</td>
<td>48</td>
</tr>
<tr>
<td>R21</td>
<td>54</td>
<td>x</td>
<td>64</td>
</tr>
<tr>
<td>T42</td>
<td>64</td>
<td>x</td>
<td>128</td>
</tr>
<tr>
<td>T95</td>
<td>144</td>
<td>x</td>
<td>288</td>
</tr>
<tr>
<td>T106</td>
<td>160</td>
<td>x</td>
<td>320</td>
</tr>
</tbody>
</table>

Table 8. Number of grid points on each horizontal level

Currently, ECMWF uses a global spectral model with T106 in the horizontal and 19 levels in the vertical for operational forecasting. Standard versions R15 and T42 of the CCM1 have 12 vertical levels. A 30-day forecast with a T42 L12 version of CCM1 takes approximately 3 GAUs in background rate on the NCAR CRAY X-MP/48, which is too expensive to run under our present allocation. Therefore, currently, most prediction experiments are conducted with a T31 L12 version which takes 0.5 GAUs in background rate for a 30-day forecast. A next-generation computer will enable us to run a T42 version of CCM1 for 30-day forecast experiments as we have done with the R15 version.

To investigate atmospheric behaviors on the order of several weeks and longer, we need to examine the role of the ocean in a coupled atmosphere-ocean-land system. Realistic values of the sensible and latent heat fluxes from the ocean to the atmosphere are needed to calculate the response of the atmospheric circulation on time scales as short as several weeks. A next-generation computer will enable us to run predictability experiments with a coupled atmosphere-ocean model. There is some reason to believe that the present limit of atmospheric predictability with atmospheric models with fixed sea surface temperatures at their initial value may have underestimated the predictability of low-frequency atmospheric variability due to the artificial
constraint of fixing the lower boundary conditions. More naturally interactive boundaries may enhance the predictability of low-frequency motions by allowing a more physical relaxation of surface boundary effects. Thus, rather than continually re-exciting low-frequency instabilities, the atmosphere-ocean-land system may mutually adjust, resulting in a more predictable system. This mutual adjustment would also lead to a greater portion of low-frequency variability being classified as boundary driven rather than dynamically driven, and thus increase the predictive signal-to-noise ratio.

2.7.4 Stochastic-dynamic Prediction Strategies

Because the time range of extended-range prediction exceeds that of deterministic predictability (approximately 12 days), it is important to indicate the level of confidence for extended-range forecasts. Uncertainties in deterministic forecasts are caused by the nonlinear nature of fluid flows coupled with many uncertainties in the physical processes operated in the models. A prediction method that can indicate the degree of forecast uncertainty during the model run while retaining the full deterministic prognostic equations as a subset is called stochastic-dynamic prediction. The ensemble mean forecast provided by the stochastic-dynamic equations will be more accurate than the deterministic forecast in the classical least-mean-square sense. Although progress has been made in the formulation of stochastic-dynamic prediction schemes to economize computing requirements, a practical execution of stochastic-dynamic prediction with a comprehensive global model may require supercomputers which are 10 to 100 times faster than the CRAY X-MP/48.

An alternative to the formal stochastic-dynamic prediction approach is the use of the Monte Carlo technique to construct ensembles of forecasts. If we construct Monte Carlo forecast ensembles starting from slightly different initial states that are created by adding random perturbations to a probable initial state, we may need on the order of 100 ensembles per forecast to simulate the statistics of the forecast ensemble expected from the formal approach. Therefore, the goal is to design a strategy to create an effective initial state ensemble from which a significant Monte Carlo
forecast ensemble can be derived. For example, by perturbing the most unstable modes of a basic state composed from a time average of a short-range forecast, one may hope to produce a more representative prediction of the variance of the forecast ensemble using trial runs on the order of 10 instead of 100.

Extensive efforts are being made by NCAR and university scientists to design different sampling strategies for the selection of initial state ensembles used in Monte Carlo forecasting in the extended range. In summary, Monte Carlo techniques have a dual purpose in extended-range forecasting: (1) dynamical smoothing of unpredictable details of forecast fields, resulting in a superior forecast of the ensemble mean, and (2) ensemble variance prediction to quantify forecast confidence and reveal multimodality of the probability distribution. However, to realize the potential gains of this technique, we must develop resourceful methods of maximizing the information obtained from small samples under the limitation of computing resources.

2.7.5 Reduction of Systematic Errors Associated with Model Climate Drift

Despite recent progress in operational medium-range prediction, many deficiencies still exist in all aspects of numerical weather prediction. The most immediate problem in extended-range forecasting is the reduction of systematic errors. It has been shown that the skill of 30-day forecasts can be improved significantly if systematic errors in the forecasts are eliminated. Forecast systematic errors are caused by the model's tendency to reach an equilibrium state different from the real climatology. This tendency is referred to as "climate drift." Research in this area, therefore, is not only of the utmost importance to forecasting, but also reaps a side benefit to climate simulation and sensitivity studies. Because of the wide variation in the time scales of the processes contributing to systematic forecast errors, and in order to address the regional aspects of this problem, it is necessary to build a case ensemble database of perhaps 30 different initial states with forecasts of 60-day duration. Furthermore, to investigate hypotheses relative to the causes of climate drift, it will be necessary to perform many forecasts from these starting times. Depending
upon the time scale of the drift relevant to the particular hypotheses, the requisite forecast length for each hypothesis may be as short as 10 days or as long as 60 days. Clearly, we wish to investigate the climate drift of CCM at its finer horizontal and vertical resolutions. In short, an exciting opportunity exists for NCAR and university scientists to advance the art of weather prediction beyond the current limit of deterministic predictability, if a faster computer becomes available.

Estimates of the resources needed for extended-range numerical weather prediction activities follow:

<table>
<thead>
<tr>
<th></th>
<th>Memory Needed</th>
<th>X-MP Single Processor hours/run</th>
<th>Number of Runs/Year</th>
<th>Annual in K Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency predictability experiments</td>
<td>20 million words</td>
<td>200 hours/run</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Stochastic-dynamic prediction strategies</td>
<td>30 million words</td>
<td>20 hours/run</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Reduction of systematic errors associated with model climatic drift</td>
<td>20 million words</td>
<td>20 hours/run</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>12</td>
</tr>
</tbody>
</table>

*Table 9. Required computer resources for numerical weather prediction activities*
3. THE SCIENTIFIC COMPUTING DIVISION

A supercomputer is defined as the highest performing scientific processor available at a given point in time. Therefore, supercomputing is difficult to precisely define because its definition changes as more powerful computers are introduced. Supercomputing, however, encompasses all of the supercomputer related activity and it may be more broadly defined as the use by a group of researchers or an institution of a system that provides the best obtainable performance (at that point in time) considering all of the variables comprising scientific computer architectures. These variables include CPU speed, memory size, I/O performance, data archival capacity, graphics, networking, and overall software performance for the mix of scientific projects of interest to that group. Perhaps a more appropriate description would be "advanced scientific computing."

Advanced scientific computing in support of the atmospheric sciences has been the focus of the NCAR Scientific Computing Division (SCD) since its formation in 1962. It has been a national facility since March 1964. It currently serves 1750 validated users. Of these, 1100 were active in FY89 (450 at NCAR and 550 from the university community).

Because of the importance NCAR attaches to computing, SCD is operated as an NCAR division on the same level as the other NCAR scientific divisions. An organization chart for the division is shown in Figure 5.
Figure 5. The SCD organization

The division director, Dr. Bill Buzbee, chairs an executive committee composed of the SCD section heads which manages the division. SCD has an advisory panel (see Attachment E) for overall policy guidance and for the allocation of resources for the external community (see Attachment F). Additionally, SCD has a technical advisory committee whose membership (see attachment G) is primarily from outside NCAR.

The allocation policy approved by UCAR and NSF assigns 44% of the resources to the external university community, 44% to the NCAR scientific staff, 10% to joint university and NCAR
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projects, and 2% to an NCAR directors reserve. The NCAR allotment is handled by the NCAR division directors committee.

SCD has pioneered efforts in graphics, mass storage and data archiving, mathematical software and networking, as well as maintained a leading edge computing engine. SCD is now evolving into full support of a distributed environment, designed to highlight the best characteristics of all the components from supercomputers to workstations, unified with a common operating system, UNIX, and presented to the user community in a convenient menued manner where the system can remain invisible for the majority of tasks. At the center of this distributed environment will be an advanced supercomputer, with an order of magnitude more capability when used in the multitasking mode and nearly two orders of magnitude more memory than the existing X-MP/48 – X-MP/18 complex. This will provide the best obtainable overall computational performance for the atmospheric and ocean science community. A diagram of the enhanced computing facility is shown in Figure 6.
Figure 6. Diagram of the enhanced computing facility
3.1 Science

The development of the General Circulation Model of the atmosphere was begun in 1964 by Warren Washington and Akira Kasahara. The GCM activity evolved beginning with simple numerical stability studies, gradually becoming more elaborate with the analysis of the importance and relevance of terms, simplifying the equations to represent the atmosphere's actual flow. With experience, finite difference schemes were exchanged for the spectral modeling techniques introduced by ECMWF. A second generation of the General Circulation Model was completed in 1969.

This model, with a 5-degree horizontal resolution and 2 layers, and its successors, became a major consumer of machines and human resources in SCD over the years and pointed the way for SCD to develop services that were beneficial to all its users. Modeling activity related to the GCM in climate and weather prediction has used 50% of the SCD resources (see Table 10). Therefore, scientists working on the GCM needed SCD services in the areas of processor characteristics, graphics, mass storage algorithm development, and system software.

By 1973, effort was put into the development of fine-mesh, limited area models to obtain short-range forecasts. These models incorporated small-scale dynamical and thermo-dynamical physics.

The GCM was made available to the atmospheric science community as a Community Climate Model in the late 1970s. NCAR imported the ECMWF model in 1981 and converted it into what is now the CCM used by many SCD users.

Table 10 shows the approximate usage of center resources by the fields of atmospheric and ocean science during selected years. GCM activity is included in the table under the headings of "climate" and "weather prediction."
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<table>
<thead>
<tr>
<th>Field</th>
<th>Percentage of Computer Resources Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrophysics</td>
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</tr>
<tr>
<td>Basic Fluid Dynamics</td>
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</tr>
<tr>
<td>Climate</td>
<td>23</td>
</tr>
<tr>
<td>Cloud Physics</td>
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<tr>
<td>Oceanography</td>
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<td>0</td>
</tr>
<tr>
<td>Weather Prediction</td>
<td>22</td>
</tr>
<tr>
<td>Other</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 10. Resource usage by field*

### 3.2 User Services

SCD continually emphasizes the needs of its users and actively solicits their input. The SCD division director and several of his staff together visit at least six university sites a year to keep in touch with user issues and to inform university users of SCD's new services and future plans.

SCD also encourages user participation in a number of advisory committees. These include:

- The SCD Advisory Panel that meets twice a year (since 1964) to assist with long-term planning and university computing allocations
- The SCD User Group that meets monthly (since ~1974) covering a broad range of issues
- The Mass Storage System Advisory Committee that meets monthly (since ~1987) and assists SCD in planning for future development of the Mass Storage System
- A user conference that is held every 18 months (since 1981). This conference covers new facilities, services, and SCD's future plans. Attendees are invited to provide input to these plans during the conference question and answer sessions.

In addition, SCD has used several special advisory groups where input was needed in specific areas. Examples are:
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- The Documentation Advisory Committee (met for eight months, with equal representation from NCAR and universities, to provide user input and advice concerning documentation for the SCD computing systems; comprehensive report issued)
- The Computer Output Committee (met for six months, with equal representation from SCD sections involved in providing computer-generated output, to recommend future directions for laser printer, microfilm, and microfiche services; report issued)

3.2.1 Consulting

User consulting is provided by highly skilled professional programmers. Consulting services are provided 38.5 hours per week via telephone, electronic mail, or in person. The SCD Consulting Office resolves over 90% of user problems the same day they are received. Users consistently rate the quality of SCD’s user support as very good or excellent (based on User Project Completion Reports).

A user area is available to SCD visitors 24 hours per day, 7 days a week, with a variety of graphics workstations and personal computers. A full set of vendor and SCD documentation is available for reference.

3.2.2 Documentation

As the complexity of the supercomputing environment has increased, so has the need for documentation. Because SCD must document local system modifications, vendor documentation is insufficient. To fill this need, SCD has developed a comprehensive set of written and online documentation with a catalog that discusses SCD and vendor documentation. This catalog is updated every six months and is distributed to all users once a year.
SCD has recently developed a new user Primer that serves as a tutorial for NCAR computer usage.
Each delineated step visually shows what the user types on the screen and how the computer responds. This greatly simplifies the introduction of the new user to the facility.

3.2.3 Training

SCD offers two types of training classes for differing user requirements. For the new user, SCD provides a one-day New User Orientation Class at NCAR or at university sites for groups of ten or more. This class is offered monthly at NCAR as a hands-on learning laboratory with an accompanying Student Workbook. By the end of the class, the student gains a basic introduction to the SCD computing environment including Cray job control language, and commands to access the Mass Storage System and output servers.

SCD also offers site liaison training for users with three to five years of experience of computing on NCAR’s machines and who support other NCAR users at their university. One representative from the 22 largest user sites and two representatives from each of NCAR’s scientific divisions are invited to an intensive week-long training session covering the Cray and Unicos operating systems, networking and data communications to/from NCAR, code optimization, graphics, the Mass Storage System, and output servers. For example, the August 1988 Site Liaison Workshop offered 32 different talks by over 30 different speakers. All speakers were SCD staff presenting information in their area of expertise. SCD covers all costs associated with this intensive training to ensure that the proper support staff are trained, regardless of departmental budgets. Site Liaison training is offered approximately every 18 months.

SCD is developing a videotape on NCAR Graphics and the GKS graphics standard from a user perspective. This 20-hour videotape will be available at low cost to universities and government agencies. SCD is also planning specialized one-week courses for university and NCAR users on optimization and multitasking.
3.2.4 Software Libraries

The SCD-supported applications software contains over 9,000 subroutines and functions, spanning 20 mathematical libraries. Requests for new software are given priority according to overall usefulness, quality of software, cost, and effort required to support the product. SCD provides both an online and printed software catalog organized by function with keyword cross-referencing.

During 1989, SCD began providing user access to portable, nonproprietary software over file transfer protocol (ftp) on a distributed software libraries server. This assists users in debugging code on workstations to and performing local graphical analysis on their data.

SCD is converting routines to support multitasking on a demand basis. SCD has also installed the SLATEC Library that supports multitasking.

3.3 Operations and Maintenance

The SCD Operations and Maintenance Section is responsible for keeping the NCAR computer center in first-rate condition. SCD operates its equipment around the clock and Operations staff are present 24 hours a day, 365 days each year. Therefore, consulting and assistance is always available for user support. Besides operating the equipment, Operations staff produce the microfilm graphics and distribute it to users. This local processing allows a two-hour turnaround time during the day. Maintenance of computing equipment and associated peripherals is performed by contracted vendor staff or in-house engineers. The SCD Maintenance Group performs maintenance for microfilm graphics, the terminal-to-computer switching unit that permits any NCAR PC or terminal to connect to any minicomputer or mainframe, all communications connections and hardware, and 700 NCAR PCs.

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The group is also available to fix almost anything electric or electronic in the NCAR inventory of equipment. The group schedules training and re-certification courses. The Operations staff assist the Maintenance Group in contracting for maintenance on the micro- and minicomputers, the Crays, IBM, and Xerox equipment.

3.4 Graphics

By the fall of 1965, SCD had attached a Data Display-80 (DD80) microfilm graphics device to a data channel of the Control Data Corporation (CDC) 3600. Normally, microfilm and other graphics devices were placed "offline." However, the online connection allowed SCD to provide excellent service and use of the DD-80 rapidly increased. The DD80 allowed SCD to launch its microfilm graphics service which was to grow in prominence as the years passed. At the end of 1965, SCD's first computer-generated weather movie was created using the DD80. In 1967, a color movie was produced by Warren Washington (NCAR/CGD) from GCM output which showed the earth with continental outlines, contoured varying pressure fields, and pressure highs and lows. NCAR was providing the atmospheric sciences with graphic capability that was generally not available to scientists in other disciplines.

The NCAR Graphics software is now in widespread use in the universities, where it was originally obtained without charge, and elsewhere. It is estimated that it is installed at 1,000 sites. The latest version based on the Graphics Kernel System (GKS) is at 400 to 500 sites.

Higher-resolution microfilm graphics (approximately an order of magnitude better than the DD80) were needed and the Dicomed system was purchased in 1978. The Dicomed Online Operating System (DOOS) software was developed over the next few years by SCD staff. This new system replaced the nonmaintainable DD80s that were removed in 1981.
In 1988, the SCD Graphics Group was expanded to include visualization activities. It also produced a UNIX-specific version of NCAR Graphics.

That same year, SCD acquired two color Dicomed film recorders and in 1989, SCD introduced a color microfilm capability based on the Computer Graphics Metafiles produced by the latest NCAR GKS software. This capability can produce 35-mm color slides and 16- or 35-mm color movies for any scientific application that uses either NCAR’s GKS graphics routines or any other GKS system that produces CGM graphics files.

In the future, interfaces will be available for the display of output from NCAR Graphics in workstation windows. A menued interface will augment the standard Fortran subroutine graphics interface and permit a level of interactivity between a dataset to be visualized and a workstation screen. Other features to be added to NCAR Graphics include:

- Color extensions to all utilities
- Utility modifications to support an interactive interface
- An X Windows interface
- Enhanced resolution in the geographic map database
- Acquisition of surface elevation and ocean floor databases
- 3-D utilities

3.4.1 Visualization

Models and field experiments have produced very large datasets with detailed information about physical processes and events that are not easily visualized by 2-D graphics. Techniques are emerging and being adapted to science that allow extended visualization and animation capabilities. These convert the data generated by the computer simulation into information about the problem
under study that cannot be readily inferred from either the raw numeric output or from conventional computer graphics.

SCD, in recognizing this trend and the importance of adopting the tools and techniques to atmospheric science, has established a visualization laboratory. NCAR and Digital Equipment Corporation (DEC) have entered into a joint research project in scientific visualization. Through a DEC grant, SCD will acquire a number of graphics workstations to serve as test platforms for visualization software. The visualization laboratory will concentrate on support for low-end workstations costing between $10K and $20K because these are more readily acquired by university departments and NCAR scientific divisions. Because the laboratory will be of a research and development nature, emphasis will be on the assessment of hardware and software products for scientific visualization, and on the building of associated tools and user interfaces. Goals include:

- Collaboration with scientific projects in the visualization of their datasets; use of these datasets to test new techniques, software, and hardware
- Evaluation of visualization software for use in distributed workstation environments
- Selection of visualization packages for users of NCAR systems
- Adaptation of NCAR Graphics to the distributed workstation environment
- Provision of a menued interface based on X Windows to visualization packages including NCAR Graphics
- Synthesis of a video animation facility to be made available for general use

3.4.2 Animation

The Graphics Group is in the design/purchase phase of an animation system. A system overview, accompanied by brief descriptions of each subsystem, follows:
A graphics workstation controls the system, providing imagery and directing the animation process through the video mastering subsystem (see Figure 7).

An Optical Memory Disk Recorder (OMDR) and a Super-Video Home System (SVHS) videotape recorder (VTR) are coupled to an animation controller. Two SVHS VTRs, a controller, and a U-matic (studio 3/4" format) tape dubbing deck comprise the video postproduction subsystem and offer basic assemble-editing capabilities. Final output will be available on VHS, SVHS, and U-matic formats. This design seeks to balance picture quality, resolution, mastering speed, and cost while providing an effective resolution of at least 400 lines.
Productivity is optimized by using the OMDR for video mastering. Unlike videotape recorders, which offer single-frame recording rates of roughly one frame every ten seconds, the OMDR can record single frames at speeds up to four frames per second which closely matches the capabilities of today's graphics workstations. The optical disk will provide the ability to randomly review image files.

The workstation may also be programmed to "script" animation sequences from the OMDR to either a color monitor or one of the VTRs, thus offering another level of post production capability. Once mastered, imagery may be transferred to conventional videotape.

3.5 Mass Storage

The computing environment needed by the atmospheric and ocean sciences is data intensive. It depends on the ability of SCD's resources to handle large amounts of data during modeling activities and requires access to extensive data archives. Therefore, NCAR's SCD has expended effort over many years to collect appropriate data and to develop the storage facilities needed to support the research effort. This section briefly reviews the history of this activity and estimates future requirements.

The introduction of the CDC 7600 into the market place caused SCD to intensify the search for a mass storage device, i.e., archival storage device, that could begin to replace the use of magnetic tapes. Such a device was needed by the mid-70s because the SCD tape library exceeded 40,000 volumes. Several devices that recorded on strips of magnetic media had been considered as early as the CDC 3600 era, but these were not very successful products. Slowly, more promising candidates appeared. These included the CDC SCROLL, the Ampex Terabit Memory (TBM) system, and a laser device, Unicon, that recorded on coated mylar strips.
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Of the devices listed, only the Ampex TBM, which recorded data on two-inch videotapes, survived. By the time the procurement procedure for the TBM was complete, IBM announced the IBM 3850 tape cartridge device which would have been suitable. The Ampex TBM system as initially delivered was a minimal configuration that could not handle SCD's storage needs. It was sufficient to permit development of the CDC 7600 interface and access software as well as allow the vendor to continue the control and catalog software development.

The TBM went through a series of upgrades that added enough hardware to keep it at the ragged edge of our needs until the 1980s. After Ampex discontinued the product in 1979, SCD's Systems Section continued to enhance the software. SCD learned how to manage large amounts of data and found that the rewrite capability on mass storage media was unnecessary. This information allowed us to review the use of optical storage in the 1980s; otherwise, it would not have been considered since it could not then be rewritten.

In 1983, SCD became interested in the optical storage unit that Storage Technology Corporation (STC) was developing and offered to participate in its testing. A preproduction model STC 7640 optical disk drive was installed at NCAR to permit software development and testing in a scientific environment. By late 1984, the optical storage unit was abandoned by STC, but SCD's design, planning, and initial implementation of the interconnection hardware and controlling software for the optical disk were of a general nature. This design permitted SCD to revert to magnetic technologies and develop a new Mass Storage System based on a large cache [120 Gigabytes (GB)] of IBM's 3380 disks, with IBM 3480 tape cartridge devices for archiving, and specially designed Network Systems Corporation (NSC) HYPERchannel adapters as network-to-storage device interfaces.

Although designed for an environment dominated by supercomputers, this new system allows for general access by any NCAR computer through the mainframe and server network (MASnet) via
the mass store control processor. Its "fast path" allows a supercomputer to move data directly to the cache and cartridges once the storage media is positioned.

The NCAR Mass Storage System is depicted in the conceptual diagram in Figure 8.

![Diagram of the NCAR Mass Storage System]

*Figure 8. NCAR Mass Storage System: conceptual view*

In spite of the overall complexity, the basic MSS concepts are simple. The MSS attempts to service data requests from the disk cache and only uses the tape cartridges when data cannot be found on the disks. A read operation is initiated from a supercomputer by sending a message via the "control path" to the control computer that immediately checks if the data is cache resident. If not, it requests that the tape cartridge containing the data be mounted; an operator then fetches the media and inserts it into any open drive. The control computer positions the media before the
desired file. The supercomputer is notified and it actually reads the file via the fast path and places the data into its own file system. (The fast path reduces the effective transfer time and allows the control computer to be considerably less powerful than necessary if it handled all the data.) If the data is cache resident, the control computer would initiate a positioning sequence on the appropriate disk and the supercomputer would move the data via the fast path. Performance and other MSS statistics are displayed in Figures 9 and 10. Note that disk cache responses which occur 67% of the time are nearly an order of magnitude faster than cartridge responses. Figure 9 shows the median response times of the MSS devices to request NCAR's supercomputers. Figure 10 shows the number of Gbytes moved per month. Figure 11 shows the growth in the average file size. Figure 12 shows the transactions by type by month.

![Graph](image)

*Figure 9. MSS reaction times for supercomputer access*
Figure 10. Gbytes moved per month

Figure 11. Growth in the average file size
Figure 12. Transactions by type by month

The following chart shows the historical growth of data archived on NCAR's mass storage systems with projections for 1991 and 1995. The table does not account for backup copies which doubled the volume of TBM data from 1976 through 1986.

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>Terabits</td>
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<td>?</td>
</tr>
</tbody>
</table>

Table 11. Data growth of the NCAR Mass Storage System

For the future, SCD needs to increase media storage space and obtain improved capacity and performance, enable the use of low-end technology for data transfer, enlarge the disk farm, and improve the networking that links the MSS components.

A single cartridge contains 200 megabytes (MB) of data. The MSS utilizes an average of 81% of this space or approximately 160 MB. At a projected growth rate of 2.8 terabytes (TB) per year,
this will add 17,500 cartridges each year. We currently have data on more than 60,000 cartridges for a total storage capacity of approximately 9.4 TB. The increase in cartridges is decreasing the available floor space in the machine room. There are three solutions to the space problem:

- The cartridge storage area may be expanded by 36% to 2,400 square feet permitting 100K cartridges to be stored in the primary storage area. This will be sufficient until mid-FY91. (Note: After mid-FY91, stricter measures will be enforced because of the impact of the upgrade.) Because half the data is long-term archival information that is rarely read, it will be moved to a distant secondary storage area.

- It is expected that the density of the IBM 3480 tape cartridge will increase to 400 MB.

- A different storage media such as VHS tape or optical disk may prove viable. VHS cartridges can provide 4 GB of storage per cartridge. Optical media capable of 4 GB per platter are under development. Both use interfaces compatible with the IBM 3480 that will allow them to be integrated into the MSS with a few modifications. However, reliability is a problem. Neither of these devices offers error rates better than one bit in $10^{12}$. Since the error rate on the IBM 3480 is better than one bit in $10^{14}$, these devices offer increased density at decreased reliability. In the long run, the data may have to be segregated into classes based on the need for absolute readability.

A Small Computer System Interface (SCSI) will be added to the MSS to allow access to inexpensive lower-speed devices and permit data to be more readily imported and exported from PCs and workstations on small compact storage media. This will better serve field research sites.

Hardware being acquired for this project includes an IBM Reduced Instruction-set Computer Technology (RT)/PC computer with an industry standard SCSI interface, an IBM 5088 high-speed adapter to connect the MSS to the RT/PC computer, and an EXAbyte 8-mm tape drive capable of

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storing 2.3 GB on a tape cartridge. Table 12 shows the characteristics of the devices that may be used for this purpose.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>CD ROM</th>
<th>EXAbyte</th>
<th>Floppy</th>
<th>OPTICAL SONY</th>
<th>OPTICAL BOSCO</th>
<th>1/2” Tape</th>
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<tr>
<td>Cost/drive($)</td>
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<tr>
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<td>30</td>
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<td>1500</td>
<td>125</td>
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<td>Media ($/Unit)</td>
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<td>7</td>
<td>1</td>
<td>270</td>
<td>50</td>
<td>10</td>
</tr>
</tbody>
</table>

*Table 12. Technology for data transfer*

The disk cache serving supercomputing at NCAR is reaching saturation. Increases in computing power and data movement requirements will impact the reaction time experienced by users who wish to read MSS resident data.

There are two candidate technologies that may provide suitable increases in disk capacity. The first uses traditional disks with improved density and bandwidth. The second is a new disk array technology.

IBM has announced upgrades of its disk Direct Access Storage Device (DASD) systems. Using these, a 50% increase in disk farm capacity to 180 GB would be attainable. By the FY91 timeframe, newer equipment should permit nearly 500 GB of storage capability.

Redundant Arrays of Inexpensive Disks (RAID) technology based on the magnetic disk technology developed for personal computers, seem to offer an attractive increase in performance, reliability, power consumption, and scalability. This direction is being examined by some manufacturers and developments will be closely followed. RAID technology offers:

- Up to 32 GB storage per unit
- Transfer speeds of 40 MB/s (20 MB/s sustained)
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- Fault tolerant operation with a theoretical Mean Time To Failure (MTTF) of 8,200,000 hours
- A small footprint (2 x 2 feet with a height of 6 feet)
- Small power consumption (500 to 1000 watts per unit)

NSC equipment has been used to link the MSS components and provide paths for both data and control information. Since the MSS was built, NSC has developed a new network adapter that should better serve in the control and data transfer processes.

Mass storage continues to be an enabling technology in the supercomputing arena. The future is clouded by the same issues (market size, complexity, mass productivity of media, capacity, etc.) that have prevented the availability of a complete commercial product in the past. Therefore, although progress will be slow, SCD will keep pace with the increasing storage demands by utilizing its software and whatever hardware becomes available, as it has done in the past.

3.6 Archiving

SCD's Data Support Section had its beginnings in 1965. Staff began to collect and format data from the NMC and other sources. A general inventory showing the number of grids available for each month for each source was published early on. The Data Support Section continues to provide data to many non-NCAR scientists, both U.S. and foreign. In 1987 and 1988, the Data Support staff prepared and sent data to nearly 40 scientific groups who were working on climate change studies for the Environmental Protection Agency (EPA).

Over the years, Data Support staff worked with many scientists, laboratories, government agencies, data centers, and countries to build, import, modify, and classify what is now a rather comprehensive archive serving the atmospheric science community. An emphasis is given to datasets that have potential for multiple uses with continuous records and that permit monitoring
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changes in the global atmosphere and oceans. Indeed, it is the best archive of analyses of atmospheric and ocean surface conditions in the world. The archive is used for major national and international atmospheric and ocean research projects. Data have been imported from the major field experiments such as the FGGE, the Monsoon Experiment (MONEX), the GARP Atlantic Tropical Experiment (GATE), etc. A set of seventy-two million ship observations from 1854 to 1979 were gathered with the cooperation of the National Oceanic and Atmospheric Administration’s (NOAA) Boulder and Asheville facilities and the U.S. Navy.

In 1985, the Data Support Section was instrumental in recovering the NOAA’s Tiros Operational Vertical Sounder data (TOVS). This data contained information about the largest warming of the Pacific Ocean temperatures in recorded history. The storage system at NOAA was closed before all of the data could be moved from the non-standard videotapes on which it had been stored to normally available media. Initially, SCD had only agreed to recover data gathered in the middle three years of a six and a half-year effort which was totally missing in the NOAA archives; but SCD deciphered the format of the videotapes and saved all the data.

By early 1989, the SCD atmospheric and ocean science archive contained 300 datasets in 35,000 files with 14 Tb of data. Annually, about 20 new datasets are added and 9 are updated. Datasets include:

- Daily grid point analysis data – Northern hemisphere surface grids from 1899; upper air grids from 1946; related monthly analyses are also available
- Upper air observed telecommunications data starting in 1962 received from selected countries; aircraft and satellite cloud winds are also included
- Surface observations – Hourly North American data from December 1976; global 3-hour synoptic data from July 1976; daily station data from 1979
- Marine ship data – Individual observations and monthly statistics
- Physical oceanographic data
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- Satellite data
- Incoherent scatter radar data for atmospheric elevations from 60 to 500 km
- GCM model output for changing CO₂; data to show climate change as CO₂ changes

Users may obtain copies of data on tape for remote use or use the data at NCAR. In 1988, 820 tapes and 140 floppy disks were sent to 300 scientists. Many scientists use the data online. The Data Support Section provides a menu of many data manipulation routines that have simplified access to the archives and permit scientists to easily move data to the array structures used in their programs.

Today the data support section has become an essential interface for the atmospheric and ocean science communities to the many world wide data gathering entities.

3.7 Mathematical Software/Computational Support

The Computational Support Section had its beginnings in 1963 when staff began to establish a library of mathematical routines. They made important contributions to our mathematical libraries in the areas of differential equations, matrix analysis, eigensystems, statistics, FFTs, roots, etc. They also conducted research into numerical algorithms used in atmospheric research. Specific examples follow.

- Gerald Browning and Professor Heinz Kriess (UCLA) have used a mathematical theory called the bounded derivative principle to develop accurate, well posed systems for atmospheric and oceanographic computations. These systems permit proper consideration of previously discarded time-dependent terms and significantly improve the numerical accuracy.

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Paul Swarztrauber developed a direct method for solving separable elliptic equations that was published in 1974, and as of 1989, remains the fastest method to date for this type of calculation. In 1977, he developed methods of cyclic reduction, Fourier analysis, and their combinations to solve Poisson's equation on a rectangle. He demonstrated that a direct solution of Poisson's equation could be obtained in much less time than previously attempted. In 1979, he published a parallel algorithm for solving general tridiagonal linear systems and he demonstrated that a system of N equations could be solved in a time proportional to \( \log N \) on a computer with N processors. In 1986, he developed several FFTs for special sequences, such as odd and even, that have sine and cosine expansions respectively and took advantage of symmetry to reduce the amount of computation. He has also developed FFTs for multiprocessors and massively parallel architectures.

Important software packages resulting from Computational Support staff efforts include:

- **FISHPACK** (Swarztrauber, Sweet, Adams); a group of routines for solving elliptic partial differential equations; over 1,300 copies have been distributed worldwide
- **FFTPACK** (Swarztrauber); a group of routines for solving symmetric FFTs. This has become part of most major mathematical libraries including the Sandia, Los Alamos, Air Force Weapons Laboratory Technical Exchange Committee (SLATEC) and the International Mathematical and Statistical Library (IMSL), and is used in most research and educational institutions.
- **SPHEREPACK** (Swarztrauber); a group of routines for harmonic analysis on the sphere
- **MUDPACK** (Adams); a group of programs for solving elliptic partial differential equations which is more general than FISHPACK

### 3.8 Communications and Networking
In the early 1970s, devices were acquired that were capable of connecting leased telephone lines to the peripheral systems of the CDC 6600 and 7600 computers. These connections were never satisfactory for a number of reasons. If a communications controller failed, it frequently caused a failure of the mainframe to which it was attached; communications software development and maintenance was performed directly on the supercomputer in a dedicated mode which adversely affected service; and communications software competed directly with scientific applications software for memory and cycles.

In 1974, a MODCOMP II minicomputer was obtained as the remote job entry (RJE) gateway. It was able to handle a variety of leased and dial-up communication lines. By 1980, university usage of SCD resources grew to 40% of the available time, with 200 remote users from 62 universities linked to SCD’s computers.

In the spring of 1981, an IBM 4341 was installed that slowly assumed the RJE activities and was a frontend computer for other divisions and universities. It was connected to a commercial communications service called Uninet that reduced communication costs for remote users. A second IBM 4341 was installed in 1983 and both were replaced by an IBM 4381 in 1986. By the late 1980s, remote access was possible over a large variety of networks.

In early 1984, a committee was formed to write a proposal for an experimental satellite data network. As a result, SCD won an award in June 1985 from the Networking section of NSF’s Office of Advanced Scientific Computing (OASC) for the development of a satellite data network. The resulting network, the University Satellite Network (USAN), has significantly extended our communications capability.
SCD now provides full network access to its supercomputers and servers from any of the various wide area networks (WANs) connected to UCARnet. These networks are: NSFNET, the National Aeronautics and Space Administration Network (SPAN), the Defense Research Internet (DRI), EDUCom's Because It's Time Network (BITNET), the Department of Energy's MFEnet, the Texas higher education institution's SESQUINET, the University of Colorado's SUPERnet, Colorado State University's WESTnet, and UCAR's USAN. Figure 13 shows the NSFNET and USAN connections at NCAR.
Figure 13. Wide area network connections at NCAR
SCD will improve the networks to which it is connected and will be involved in routing developments and performance monitoring. USAN, the NCAR regional network, will be improved. Dynamic routing and comprehensive monitoring will be added. A USAN site will be installed in Mexico. Other potential sites are at Pennsylvania State University and the University of Texas.

SCD is involved in the planning of a Metropolitan Area Network experiment with US West (the local phone company) that will link academic and industrial sites in the Colorado front range area with T3 [45 megabits (mb) per second] service.

3.9 Distributed Computing

User access methods to the NCAR supercomputing resources are changing. Typically, users accessed the supercomputers, archival storage, and the microfilm services through dialup and leased lines, or commercial packet services into a frontend computer connected to MASnet. The frontend machine provided batch and interactive access to the supercomputers, permitted editing and quick-look graphics, transmitted output, and performed miscellaneous functions.

The development and availability of campus networks interconnected with regional networks, NSFNET, and other national networks, have significantly improved the access over that available a few years ago. Scientists on campus networks now have terminals that range from PCs to powerful workstations that make possible a distribution of the functionality that was once centralized. SCD’s goal is to have its computing resources appear as an extension of the user’s node.

To achieve this goal, SCD is working on a uniform workstation window user interface (WWUI). The advantage of window managers is that one user can simultaneously run and monitor a number of tasks. Users can interact with tasks by the windows assigned to each. SCD will supply an X
Windows version of the WWUI on any UNIX-based workstation, for the MAC and PC MS-DOS stations. The WWUI will provide the following functions:

- Logon access to SCD systems
- Interactive and batch access to SCD systems
- Asynchronous access to files and file archives and the ability to move files anywhere in the distributed environment
- Editing and interactive display of text, graphics, and visual information on workstations
- Use of local high quality graphics output devices
- A command interface for defining macros which can send native job control language (JCL) commands to systems in the distributed environment. SCD will supply a generic set of commands to perform common functions for file access, compile load and go sequences, archival access, and quick-look graphics
- A menu of the most used JCL programs for network, graphics, archive access, control sequences, etc., and the ability to make all functions readily available so that the operating systems may be hidden if the user wishes to achieve anonymity

The future thrust of distributed computing will be to encourage as much developmental work as possible on workstations, minicomputers, and minisupercomputers to reduce the overhead of job preparation and postprocessing tasks on the main supercomputers.

3.10 Computers

Table 13 summarizes the characteristics and estimates the increase in capability for each of the supercomputers that have generally supported atmospheric and ocean science at NCAR. It also shows the performance increase expected as a result of the upgrade in 1991.
In 1989, the single-processor CRAY X-MP/18 replaced the original CRAY-1A and was used as a bridge to the UNIX operating system that will be the only operating system in use on SCD supercomputers in the 90s.

However, our activities have not been limited to standard supercomputer architectures. In September 1988, SCD became the operational facility for the University of Colorado's Center for Applied Parallel Processing (CAPP) with the installation of a connection machine model CM-2 made by Thinking Machines Corporation. Our membership in CAPP has provided us with an up-to-date test bed for applications on a massively parallel system.

In 1988, Paul Swarztrauber and Dick Sato from SCD's Computational Support Section established a parallel geodynamics project to provide information on the suitability of the CM-2's single-instruction-multiple-data-stream (SIMD) architecture for modeling atmospheric science problems. It has run the shallow-water equations on cartesian coordinates using finite difference methods. For this idealized problem, a speed of 1.3 billion floating point operations per second (Gflops) was obtained when the results were scaled from the available 8K processors to a 65K processor system. The next step was to implement a spectral method solution to the same equations. Results were good enough to attempt to implement these equations using spherical geometry. Therefore, the presence of the CM-2 at NCAR is providing an opportunity to test this technology that is
believed by some to be scalable to the trillion floating point operations per second (Teraflop) performance level. By the summer of 1989, the parallel geodynamics project is expected to evolve into a joint effort with the ECMWF. CAPP and NCAR's SCD are actively seeking support to upgrade the CM-2 to a 32K processor system with increased memory on each processor. Also, it is anticipated that the machine will be upgraded to a CM-3 in the early 1990s. Therefore, NCAR's SCD will remain at the forefront of both shared memory multiprocessor and massively parallel supercomputer architectures.

3.11 Summary

SCD provides the atmospheric and oceanic sciences with a supercomputing environment that is tailored to their needs. Attributes of that environment include:

- large memory capacity
- high-performance mass storage
- state-of-the-art distributing capacity
- state-of-the-art graphics and visualization
- remote access via national networks
- data archives
- consulting, documentation, and training
4. ISSUES

There are a number of issues that must be addressed regarding supercomputing at NCAR. These issues are related to the changes brought about by the establishment of the NSF National Supercomputer Centers, the rapid increase in the number of state-supported centers, and the impact of very powerful workstations and minisupercomputers.

4.1 Availability of Resources at the Five NSF National Centers

Resources are available at the five other NSF national centers: the San Diego Supercomputer Center [SDSC (California)], the National Center for Supercomputing Applications [NCSA (Illinois)], the Cornell Theory Center/Cornell National Supercomputer Center (New York), the John von Neumann Computer Center [JVNCC (New Jersey)], and the Pittsburgh Supercomputer Center [PSC (Pennsylvania)]. Currently, any U.S. academic scientist may obtain computer time at one of these centers provided that the research is not classified, proprietary, or medical. The NSF DASC allocation policies at these centers are described in Attachment E. The procedure is similar to obtaining resources at SCD. The scientist submits a proposal to the center for review. Depending on the magnitude of the request, it may be granted by the center director, sent out for mail review, or reviewed and presented to a multidisciplinary review panel. The categories vary somewhat, but typically they are 5 hours, 50 to 100 hours, and over 100 hours respectively.

In FY88, atmospheric sciences used about 5% of the resources (service units) at the other NSF centers. Table 14 shows the usage in hours by the atmospheric sciences and oceanography since the centers opened in 1986.
Most of this usage occurred at SDSC and PSC. Annually, each processor of a multiprocessor machine can provide about 7,500 hours of time. Therefore, at its peak in FY88, atmospheric and ocean sciences used about an X-MP processor equivalent of time out of approximately 19 available. As shown by Table 15, there will be considerably more equivalent X-MP processors available in the following years. Proposal review panels try to balance the usage among the disciplines. In other words, allocations of time should be available to perhaps 10% of the total time available based on past usage by the geosciences.

| X-MP/18 Equiv. Processors Available at DASC Centers |
|------------------|----------|----------|----------|----------|----------|----------|
| 8     | 15    | 19    | 40    | E60   | E120  |

There are problems with these projections, however. Performance estimates for the ETA 10 and IBM 3090, comparing them to a single processor of a CRAY X-MP/18, are inexact. The delivery time of the first CRAY-3 to these centers may be later than in mid-1990 as estimated in Table 15. The portion of time available to the U.S. scientific research community at these centers may be less than it was in the past because the portion of DASC funding as a percentage of their overall funding may decline. If the decline is significant, the availability of time will necessarily be affected. However, this community should be able to obtain the equivalent of four processors of X-MP time by late FY89; perhaps increasing to a Y-MP/8 by 1991.

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The NSF allocation policy may change. Discussions have occurred regarding the placement of allocations back into the NSF directorates and instituting chargebacks to them sometime around FY93. In this case, NSF’s Geosciences Directorate (GEO) would allocate funds to the Atmospheric Sciences Division (ATM) to pay for the usage from its budget, effectively eliminating the current relatively advantageous system.

The other NSF centers do not have some of the facilities and resources provided at NCAR. For example, they do not have our mass storage facilities. The absence of mass storage facilities and the NCAR data archives will present a problem to many of the NCAR users when attempting to use non-NCAR facilities, making migration to other centers impractical. However, in the 1990 timeframe, when the network backbone begins operation at T3 rates, remote access to the NCAR data by modelers running elsewhere may be more feasible than now; but we believe that even then, it will be easier to process this data at NCAR. NCAR is the leader in the graphics services needed by the atmospheric and ocean sciences. The latest version of the Community Climate Model is only available at NCAR.

NCAR’s Scientific Computing Division provides a disciplinary focus that is unique among NSF-supported computing centers. While it is true that any well run supercomputer center must have the same auxiliary services that exist at SCD, the emphasis on the needs of the community is qualitatively different in SCD. SCD provides the essential data support and archival services necessary to conduct atmospheric and ocean science research. Hardware configurations, software systems (including schedulers) tuned for heavy data movement conditions, graphics and visualization services, algorithm development, indeed, the entire Operations and User Services structure, are dedicated to the support of these disciplines.

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4.2 Impact and Usage at the State-supported Independent University Centers

There are a number of independent university centers where it is possible for the community to obtain time whenever data, graphics, and software such as the CCM do not force the user to remain at NCAR. The use of the NCAR center by the university community declined from a high of 43% in FY83 to 31% in FY88. It is believed that this decline could be attributed to the allocation process that may have underallocated the university users resulting in their heavy use of background queues. Between FY86 and FY88, users from an average of 67 institutions utilized NCAR's facilities. Table 16 lists 27 institutions with their supercomputing equipment that should be available by the end of FY89. These institutions will then have about 64 single processor X-MP equivalents available which is an increase from about 5 in 1986. Researchers at the ten institutions with an asterisk used NCAR resources during FY88 and the first half of FY89. Many of these machines have relatively small capacities. Most of these computing centers have limited data archives and storage facilities. So, it will take some time to determine if a significant number of university users will migrate back to their home institutions.
<table>
<thead>
<tr>
<th>Institution</th>
<th>Equipment</th>
<th>NCAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>CRAY X-MP/24</td>
<td>*</td>
</tr>
<tr>
<td>Arizona State</td>
<td>IBM 3090/500/3VF, CRAY X-MP/14</td>
<td></td>
</tr>
<tr>
<td>Boston U.</td>
<td>IBM 3090/200/2VF</td>
<td></td>
</tr>
<tr>
<td>Colorado State</td>
<td>CY205</td>
<td></td>
</tr>
<tr>
<td>Cornell</td>
<td>IBM 3090/200/2VF</td>
<td></td>
</tr>
<tr>
<td>CUNY</td>
<td>IBM 3090/200/2VF</td>
<td></td>
</tr>
<tr>
<td>Florida</td>
<td>IBM 3090/400/3VF</td>
<td></td>
</tr>
<tr>
<td>Florida State</td>
<td>ETA-10/4E</td>
<td></td>
</tr>
<tr>
<td>Georgia</td>
<td>ETA-10/Q2, CY205, IBM 3090400E/3VF</td>
<td></td>
</tr>
<tr>
<td>HARC</td>
<td>NEC SX2</td>
<td></td>
</tr>
<tr>
<td>Kentucky</td>
<td>IBM 3090/300E/3VF</td>
<td></td>
</tr>
<tr>
<td>Michigan</td>
<td>IBM 3090/600E/2VF</td>
<td></td>
</tr>
<tr>
<td>Minnesota</td>
<td>CRAY-2, ETA-10/4E</td>
<td></td>
</tr>
<tr>
<td>Mississippi</td>
<td>CY205</td>
<td></td>
</tr>
<tr>
<td>MIT</td>
<td>CRAY-2/4-256</td>
<td></td>
</tr>
<tr>
<td>N. Carolina SCC</td>
<td>CRAY YMP4/32</td>
<td></td>
</tr>
<tr>
<td>Ohio State</td>
<td>CRAY YMP8/32</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>IBM 3090/200E/2VF</td>
<td></td>
</tr>
<tr>
<td>Penn State</td>
<td>IBM 3090/400E/2VF</td>
<td></td>
</tr>
<tr>
<td>Purdue</td>
<td>ETA 10/P, CY205</td>
<td></td>
</tr>
<tr>
<td>Scripps Institute</td>
<td>CRAY SE</td>
<td></td>
</tr>
<tr>
<td>Stanford</td>
<td>IBM 3090/300E/3VF, 3090/300E/2VF</td>
<td></td>
</tr>
<tr>
<td>Tennessee</td>
<td>IBM 3090/200E/2VF</td>
<td></td>
</tr>
<tr>
<td>Texas</td>
<td>CRAY X-MP/24, CRAY SE</td>
<td></td>
</tr>
<tr>
<td>UC-Berkeley</td>
<td>CRAY X-MP/14, IBM 3090/200/2VF</td>
<td></td>
</tr>
<tr>
<td>UCLA</td>
<td>IBM 3090/200/2VF</td>
<td></td>
</tr>
<tr>
<td>VPI</td>
<td>IBM 3090/200/2VF*</td>
<td></td>
</tr>
</tbody>
</table>

*used NCAR resources during FY88-89

Table 16. Availability of supercomputing equipment by the end of FY89

4.3 Impact and Usage of Workstations and Minisupercomputers

By the end of 1988, minisupercomputer vendors had sold about 1,500 systems. Three vendors accounted for the majority of these. If these minisupercomputers are configured with comparable memory, rough service equivalency with supercomputers occurs when turnaround is the same. Workstations number in the hundreds of thousands. Table 17 shows some performance ratios for computers in different classes.
<table>
<thead>
<tr>
<th>Types of Devices</th>
<th>Shallow Water Model</th>
<th>Community Climate Model</th>
<th>Linpack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercomputers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEC SX2</td>
<td>2.4</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>CRAY X-MP</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>ETA 10E</td>
<td>0.9</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>IBM 3090 600E/VF</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Minisupercomputers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alliant FX80</td>
<td>(6) 0.2</td>
<td>(4) 0.09</td>
<td>(8) 0.1</td>
</tr>
<tr>
<td>Ardent</td>
<td>(2) 0.1</td>
<td>(1) 0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>Convex C210</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>FPS 264</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Multiflow</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>SCS 40</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Workstations</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SUN 4/280</td>
<td>0.01</td>
<td>0.03</td>
<td>(260+FPA) 0.008</td>
</tr>
<tr>
<td>SUN 3/280S</td>
<td>0.007</td>
<td>-</td>
<td>0.006</td>
</tr>
<tr>
<td>IBM PC/RT</td>
<td>0.003</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Minicomputers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBM 4381/P14</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>DEC VAX 8550</td>
<td>0.009</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Values in parenthesis indicate number of processors used. (Data for Shallow Water Model and Community Climate Models from R.K. Sato. Linpack results from "Performance of Various Computers Using Standard Linear Equations Software in a Fortran Environment" by J. Dongarra.)

*Table 17. Ratios from benchmarks (performance x 1 processor of an 8.5ns X-MP)*

This table indicates that a typical minisupercomputer runs at about 10% of the rate of an X-MP single processor. High performance workstations run at 1% to 2% of the X-MP single processor.

In general, workstations and minisupercomputers do not have the processing speed and memory capacity required by the projects discussed in Section 2. Minisupercomputers and workstations will remain important components of the distributed environment because they are a convenient platform for model and algorithm development, debugging, visualization and output perusal. Moreover their performance increases significantly each year and some part of the projected workload will be undertaken using these tools.
Occasionally the argument arises that large scale supercomputers are no longer necessary. The current large-scale scientific computing paradigm is one which has a supercomputer operated centrally, supported by a professional staff, with archival mass storage, hard copy graphics and networked to a distributed environment consisting of many terminals, PCs, workstations and a relatively small number of minisupercomputers. It should be noted that in the case of NCAR’s SCD that the archival capability includes both the data and the support that would be found at an excellent data center dedicated to the atmospheric and ocean sciences. In the revised view the supercomputer would give way to a large number of minisupercomputers liberally distributed and without the need for the professional staff; in effect giving each scientist a system.

Indeed this seems a very appealing solution to the problems of centralization. However would such a solution be practical or achievable at comparable cost? Based on costs and other considerations, a conclusive "no" must be given. This document shows the atmospheric and oceanographic scientific computing requirement in the coming years for NCAR and the universities at the rough equivalent of five CRAY-3s. Memory requirements range from ten million words up to 100+ million words. Assuming for the moment that all of the requested capability were provided, the following table makes clear the infeasibility of a total minisupercomputer solution:

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Annual Maintenance</th>
<th>Estimated Systems Required</th>
<th>Total Cost</th>
<th>Total Maintenance</th>
<th>Estimated Staff</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRAY-3</td>
<td>35.0</td>
<td>1.00</td>
<td>5</td>
<td>175</td>
<td>5</td>
<td>105</td>
</tr>
<tr>
<td>Ardent Titan</td>
<td>0.1</td>
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<td>3700</td>
<td>370</td>
<td></td>
<td>600</td>
</tr>
<tr>
<td>Convex(210)</td>
<td>0.7</td>
<td>0.06</td>
<td>960</td>
<td>580</td>
<td>60</td>
<td>300</td>
</tr>
</tbody>
</table>

(All $ M)

Table 18.
This table is based on an estimated per processor performance ratio (next generation supercomputer to XMP) of 3:1 and it averages the shallow water model and community climate values in table 17 for the performance ratios of the minisupercomputers compared to a single processor of the CRAY X-MP/48. The maximum memories of the minisupercomputers used in the table range from 16 to 256 megawords, but at these larger memory sizes, which are required for the science outlined herein, substantial increases in system price occur. Smaller one to eight megaword systems have been used in the comparison table because these sizes were available as benchmarking systems. Staffing for the minisupercomputers is assumed at 0.25 FTEs each and this may be too low if there is a substantial geographic spread among the systems or if their users want customized systems.

It is frequently asserted that other architectures are more appropriate for the work described herein than one of the multi-processor shared-memory supercomputers that is sought as an upgrade to the existing CRAY X-MP/48. These generally fall into the class of massively parallel systems. However at this time and for the time frame involved, the software systems are not robust and probably will not advance to the necessary level of capability. Also much algorithm development remains. Therefore such equipment will remain at best experimental during the next 5 years. NCAR's SCD will continue to experiment with these systems, especially the Connection Machine, but general service will continue to be offered on more conventional systems.

4.4 Summary

4.4.1 Availability of resources at the other NSF National Supercomputer Centers

Based on past usage of these centers by atmospheric and oceanic sciences, this community can probably obtain the equivalent of a Y-MP/8 by 1991 at these centers. This is about 7% of the total capacity requested in this document.
4.4.2 Usage of state-supported centers

While these centers will be accessible to this community, the capability of these centers is generally inadequate to meet our needs.

4.4.3 Usage of workstations and minisupercomputers

Workstations and minisupercomputers will certainly be a useful part of the distributed environment and will serve to enhance the capability and effectiveness of the next generation supercomputer at NCAR.
5. BUDGET

Table 19 shows the estimated incremental cost of the enhanced computing facilities at NCAR.

<table>
<thead>
<tr>
<th>Items</th>
<th>91</th>
<th>92</th>
<th>93</th>
<th>94</th>
<th>95</th>
<th>96</th>
<th>97</th>
<th>98</th>
<th>99</th>
<th>00</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRAY X-MP/18</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1991 Supercomputer (1)</td>
<td>5.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>5.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995 Supercomputer (2)</td>
<td></td>
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<td></td>
<td></td>
<td>7.50</td>
<td>15.00</td>
<td>15.00</td>
<td>15.00</td>
<td>7.50</td>
<td></td>
</tr>
<tr>
<td>1999 Supercomputer (3)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.50</td>
<td>22.50</td>
<td></td>
</tr>
<tr>
<td>Distributed Computing (3)</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Maintenance and Software Licenses (4)</td>
<td>0.90</td>
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<td>2.50</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.25</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>8.15</td>
<td>13.05</td>
<td>13.05</td>
<td>13.05</td>
<td>16.25</td>
<td>19.25</td>
<td>19.25</td>
<td>19.25</td>
<td>23.50</td>
<td>27.25</td>
</tr>
</tbody>
</table>

Table 19. SCD's 1991-2000 capital equipment requirements for computing ($ in millions)

(1) Includes supercomputer and secondary storage, MSS upgrade, and upgrade to Local Data Network with total purchase price of $36M

(2) Assumes each system will cost 50% more than its predecessor and will offer an order of magnitude more capability

(3) This budget item is funding for high-performance workstations that are needed to use with the next generation supercomputer in a distributed computing environment.

(4) Includes supercomputer, MSS equipment, and Local Data Network
## Attachment A. Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACA</td>
<td>Atmospheric Chemistry of Aersols</td>
</tr>
<tr>
<td>ACM</td>
<td>Atmospheric Chemical Modeling</td>
</tr>
<tr>
<td>AKP</td>
<td>Atmospheric Kinetics and Photochemistry</td>
</tr>
<tr>
<td>AON</td>
<td>Atmospheric Odd Nitrogen Species</td>
</tr>
<tr>
<td>ATM</td>
<td>Atmospheric Sciences Division</td>
</tr>
<tr>
<td>BAI</td>
<td>Biosphere-atmosphere Interactions</td>
</tr>
<tr>
<td>BATS</td>
<td>Biosphere-atmosphere Transfer Scheme</td>
</tr>
<tr>
<td>BITNET</td>
<td>Because It's Time Network</td>
</tr>
<tr>
<td>CAPP</td>
<td>Center for Applied Parallel Processing</td>
</tr>
<tr>
<td>CCM</td>
<td>Community Climate Model</td>
</tr>
<tr>
<td>CDC</td>
<td>Control Data Corporation</td>
</tr>
<tr>
<td>CEDAR</td>
<td>Coupled Energetics and Dynamics of Atmospheric Regions</td>
</tr>
<tr>
<td>CGD</td>
<td>Climate and Global Dynamics Division</td>
</tr>
<tr>
<td>CINDE</td>
<td>Convection Initiation and Downburst Experiment</td>
</tr>
<tr>
<td>CME</td>
<td>Community Modeling Effort</td>
</tr>
<tr>
<td>CMEs</td>
<td>Coronal Mass Ejections</td>
</tr>
<tr>
<td>CPU</td>
<td>Cray Central Processing Unit</td>
</tr>
<tr>
<td>CSMI</td>
<td>Climate Systems Modeling Initiative</td>
</tr>
<tr>
<td>CTM</td>
<td>Chemical/transport Model</td>
</tr>
<tr>
<td>DASD</td>
<td>Direct Access Storage Device</td>
</tr>
<tr>
<td>DD80</td>
<td>Data Display-80</td>
</tr>
<tr>
<td>DEC</td>
<td>Digital Equipment Corporation</td>
</tr>
<tr>
<td>DNS</td>
<td>Direct Numerical Simulation</td>
</tr>
<tr>
<td>DOOS</td>
<td>Dicomed Online Operating System</td>
</tr>
<tr>
<td>DRI</td>
<td>Defense Research Internet</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium Range Weather Forecasts</td>
</tr>
<tr>
<td>EGCMs</td>
<td>Eddy-resolved General Circulation Models</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
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<td>----------------------------------------------</td>
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<tr>
<td>ENSO</td>
<td>El Niño/Southern Oscillation</td>
</tr>
<tr>
<td>Eos</td>
<td>Earth Observing System</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>ERBE</td>
<td>Earth Radiation Budget Experiment</td>
</tr>
<tr>
<td>EUV</td>
<td>Extreme Ultra-violet</td>
</tr>
<tr>
<td>FFRDC</td>
<td>Federally Funded Research and Development Center</td>
</tr>
<tr>
<td>FGGE</td>
<td>First GARP Global Experiment</td>
</tr>
<tr>
<td>ftp</td>
<td>File Transfer Protocol</td>
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<tr>
<td>GARP</td>
<td>Global Atmospheric Research Program</td>
</tr>
<tr>
<td>GATE</td>
<td>The GARP Atlantic Tropical</td>
</tr>
<tr>
<td>GB</td>
<td>Gigabytes</td>
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<tr>
<td>GEO</td>
<td>NSF's Geosciences Directorate</td>
</tr>
<tr>
<td>GEOSAT</td>
<td></td>
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<tr>
<td>Gflops</td>
<td>Gigaflops</td>
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<tr>
<td>GKS</td>
<td>Graphics Kernel System</td>
</tr>
<tr>
<td>GOESNEXT</td>
<td>Geostationary Operational Environmental Satellite/</td>
</tr>
<tr>
<td>GOM</td>
<td>Global Observations and Modeling</td>
</tr>
<tr>
<td>GONG</td>
<td>Global Oscillations Network Group</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/output</td>
</tr>
<tr>
<td>IMSL</td>
<td>International Mathematical and Statistical Library</td>
</tr>
<tr>
<td>LES</td>
<td>Large-eddy Simulations</td>
</tr>
<tr>
<td>LIMS</td>
<td>Limb Infrared Monitor of the Stratosphere</td>
</tr>
<tr>
<td>LTE</td>
<td>Local Thermodynamic Equilibrium</td>
</tr>
<tr>
<td>MASnet</td>
<td>Mainframe and Server Network</td>
</tr>
<tr>
<td>mb</td>
<td>Megabits</td>
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<tr>
<td>MB</td>
<td>Megabytes</td>
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<tr>
<td>MHD</td>
<td>Magnetohydrodynamics</td>
</tr>
<tr>
<td>MONEX</td>
<td>The Monsoon Experiment</td>
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<tr>
<td>9/1/89</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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</tr>
<tr>
<td>MTTF</td>
<td>Mean-Time-To-Failure</td>
</tr>
<tr>
<td>N-SCAT</td>
<td>NASA Scatterometer</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NCSA</td>
<td>National Center for Supercomputing Applications</td>
</tr>
<tr>
<td>NEXRAD</td>
<td>Next Generation Weather Radar</td>
</tr>
<tr>
<td>NLTE</td>
<td>Non-local Thermodynamic Equilibrium</td>
</tr>
<tr>
<td>NMC</td>
<td>National Meteorological Center</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NSC</td>
<td>Network Systems Corporation</td>
</tr>
<tr>
<td>OASC</td>
<td>Office of Advanced Scientific Computing</td>
</tr>
<tr>
<td>OGCMs</td>
<td>Ocean General Circulation Models</td>
</tr>
<tr>
<td>OMDR</td>
<td>Optical Memory Disk Recorder</td>
</tr>
<tr>
<td>OT</td>
<td>Optical Techniques</td>
</tr>
<tr>
<td>PBL</td>
<td>Planetary Boundary Layer</td>
</tr>
<tr>
<td>PPM</td>
<td>Pittsburgh Supercomputer Center</td>
</tr>
<tr>
<td>RAID</td>
<td>Redundant Arrays of Inexpensive Disks</td>
</tr>
<tr>
<td>RGP</td>
<td>Reactive Gases and Particles</td>
</tr>
<tr>
<td>RISC</td>
<td>Reduced Instruction-set Computer</td>
</tr>
<tr>
<td>RJE</td>
<td>Remote Job Entry</td>
</tr>
<tr>
<td>RNG</td>
<td>Renormalization Group</td>
</tr>
<tr>
<td>RT/PC</td>
<td>RISC Technology/Personal Computer</td>
</tr>
<tr>
<td>SCD</td>
<td>Scientific Computing Division</td>
</tr>
<tr>
<td>SCSI</td>
<td>Small Computer System Interface</td>
</tr>
<tr>
<td>SDSC</td>
<td>San Diego Supercomputer Center</td>
</tr>
<tr>
<td>SEASAT</td>
<td>Stratospheric General Circulation with Chemistry Project</td>
</tr>
<tr>
<td>SGCCP</td>
<td>Single-Instruction-Multiple-Data-Stream</td>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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</thead>
<tbody>
<tr>
<td>SLATEC</td>
<td>Sandy, Los Alamos, Air Force Weapons Laboratory Technical Exchange Committee</td>
</tr>
<tr>
<td>SOHO/10I</td>
<td>Solar Orbiting Heliospheric Observatory/Solar Oscillations Instrument</td>
</tr>
<tr>
<td>SPAN</td>
<td>Space Physics Analysis Network</td>
</tr>
<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
</tr>
<tr>
<td>STORM</td>
<td>stormscale Operational and Research Meteorology</td>
</tr>
<tr>
<td>SVHS</td>
<td>Super-video Home System</td>
</tr>
<tr>
<td>TB</td>
<td>Terabytes</td>
</tr>
<tr>
<td>TGCM</td>
<td>Thermospheric General Circulation Model</td>
</tr>
<tr>
<td>TIGCM</td>
<td>Thermosphere/Ionosphere General Circulation Model</td>
</tr>
<tr>
<td>TOGA</td>
<td>Tropical Oceans Global Atmosphere</td>
</tr>
<tr>
<td>TOPEX</td>
<td>Topographic Ocean Experiment</td>
</tr>
<tr>
<td>TOVS</td>
<td>Tiros Operational Vertical Sounder</td>
</tr>
<tr>
<td>TRACS</td>
<td>Trends in Atmospheric Constituents Study</td>
</tr>
<tr>
<td>UARS</td>
<td>Upper Atmosphere Research Satellite</td>
</tr>
<tr>
<td>USAN</td>
<td>University Satellite Network</td>
</tr>
<tr>
<td>VTR</td>
<td>Videotape Recorder</td>
</tr>
<tr>
<td>WANs</td>
<td>Wide Area Networks</td>
</tr>
<tr>
<td>WOCE</td>
<td>World Ocean Circulation Experiment</td>
</tr>
<tr>
<td>WWUI</td>
<td>Workstation Window User Interface</td>
</tr>
</tbody>
</table>
Attachment B. Research Collaborators

Climate Modeling Section

B. Albrecht (Pennsylvania State University), atmospheric boundary layer, free convection parameterizations
E. Cess (State University of New York, Stony Brook), radiation intercomparison
L. Donner (University of Chicago), ice-cloud parameterization cumulus initialization
S. Fels (Geophysical Fluid Dynamics Laboratory), line-by-line and narrow-band model intercomparison, general circulation model response to external heating
R. Garcia (Atmospheric Chemistry Division), two-dimensional modeling of the stratosphere
J. Gille (Atmospheric Chemistry Division, stratospheric dynamics and transport
A. Heymsfeld (Mesoscale and Microscale Meteorology Division), ice-cloud parameterization
M. Hitchman (Atmospheric Chemistry Division), stratospheric dynamics and transport
T. Hogan and T. Rosmond (Naval Environmental Prediction Research Facility), moisture transport, normal-mode initialization
J. Holton (University of Washington), stratospheric modeling
J. McConnell (York University), three-dimensional modeling
V. Ramanathan (University of Chicago), Earth Radiation Budget Experiment (ERBE)
J. Sela (National Meteorological Center), semi-Lagrangian transport
S. Solomon (NOAA, Aeronomy Laboratory), stratospheric dynamics and transport

Climate Analysis Section

P. Arkin (NOAA Climate Analysis Center), current circulation data and the 1988 drought
S.-C. Chen (Scripps Institution of Oceanography), planetary wave modeling
J. Christy (University of Alabama), atmospheric mass variations
J. Coakley (Oregon State University), cloud-climate interactions
D. Gutzler (Atmospheric and Environmental Research, Inc., Cambridge), structure of the 40- to 50-day oscillation
I. Held (Geophysical Fluid Dynamics Laboratory), wave dynamics
J. Kidson (New Zealand Meteorological Service), general circulation statistics
G. Kiladis (Cooperative Institute for Research in Environmental Sciences), tropical climatology
K. Labitzke (University of Berlin), quasi-biennial oscillation and southern oscillation in the stratosphere
H. Lejenäs (University of Stockholm), observational studies on blocking
V. Ramanathan (University of Chicago), ERBE
W. Randel (Atmospheric Chemistry Division), stratospheric and tropospheric dynamics observational studies
E. Rasmusson (University of Maryland), El Niño – southern oscillation
J. Slingo (European Centre for Medium-Range Weather Forecasts), CCM development
P. Speth (Institute for Geophysics and Meteorology, Cologne), large-scale waves
H. von Storch (Max Planck Institute for Meteorology, Hamburg), sensitivity and simulation studies

Environmental and Societal Impacts Group

E. Antal (Hungary), United States/Hungarian Great Plains
R. Benedick (Conservation Foundation), ozone depletion
P.-S. Chu (University of Hawaii), teleconnections
S. Cohen (Environment Canada), climate impacts and the Great Lakes
T. Farago (Hungary), United States/Hungarian Great Plains
A. Gromyko (Union of Soviet Socialist Republics), drought and development

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C. Howe (University of Colorado), water resources
A. Kneese (Resources for the Future), fisheries management
K. Lee (University of Washington), policy aspects of climate change
M. Lofchie (University of California, Los Angeles), drought and development
A. Maglhaes (Brazil), drought, and development in Brazil
J. McCann (Boston University), drought and development
N. Ninh (University of Hanoi, Vietnam), climate impacts in Southeast Asia
A. Nobre (Brazil), climate impacts in the citrus industry
D. Wilhite (University of Nebraska), drought and development; United States/Hungarian Great Plains
T. Wodajo (Ethiopia), drought/famine early warning systems

Global Dynamics Section

F. Carr (University of Oklahoma), forecast verification methodology and predictability
L. Donner (University of Chicago), incorporation of cumulus convection into initialization
C. Elson (Ithaca College), statistical interpretation of mesoscale model simulations
J. Geisler (University of Utah), theory of 30- to 60-day oscillation
M. Ghil (University of California, Los Angeles), theory of low-frequency dynamics
E. Kalnay (NMC, NOAA), medium-range forecast
J. Paegle (University of Utah and J.N. Paegle (University of Utah), tropical-midlatitude error interaction in medium-range forecasts
G. Platzman (University of Chicago), vertical structure equation
P. Silvia Dias (University of Sao Paulo), tropical and midlatitude interactions
K. Weickmann (NOAA), 30- to 60-day oscillation in the CCM

Interdisciplinary Climate Systems Section

W. Berger (Scripps Institution of Oceanography), paleocomposition and paleoclimate
P. Boston (NASA Langley) and C. Stoker (NASA Ames), simulation of a hypothetical Jovian microbial biosphere
C. Covey (Lawrence Livermore National Laboratory), development of an ocean mixed layer and sea ice model for CCM1
P. Crutzen (Max Planck Institute for Chemistry, FRG), stratospheric ozone perturbations from massive smoke and NOx injections
H. Dalfes (Research Institute for Basic Sciences, Turkey), core sampling simulation and simulated climatic variability
D. Erickson (Scripps Institution of Oceanography), ocean surface wind observations and variability
D. Gates (University of Michigan), development of a hierarchy of land-surface models
B. Hanson (University of Michigan), development of coupled ice sheet/climate models
J. Harte (University of California, Berkeley), biology
L. Harvey (University of Toronto), climate modeling
A. Henderson-Sellers (Macquarie University, Australia), datasets for land-surface climate studies
B. Henderson-Sellers (University of Liverpool, England), coupling the biosphere-atmosphere transfer scheme to inland areas model
J. Hopwood (University of W. Australia), dust lofting and transport parameterization
J. Kutzbach (University of Wisconsin), simulations and paleoclimatic effects of atmospheric dust transport
P. Sellers (University of Maryland), general circulation modeling of land vegetation
J.-P. van Ypersele (Catholic University of Louvain), sea-ice modeling
Oceanography Section

D. Boudra (University of Miami), ocean numerical modeling
D. Boyer (University of Wyoming) laboratory experimentation
M. Cane (Lamont-Doherty), equatorial thermodynamic model
D. Haidvogel (Johns Hopkins University), general circulation modeling
M. Melander (University of Pittsburgh), numerical modeling
P. Rizzoli (Massachusetts Institute of Technology), data insertion and assimilation
W. Schmitz (Woods Hole Oceanographic Institution), North Atlantic circulation studies
L. Talley (Scripps Institution of Oceanography), energy radiation in ocean models
G. Vallis (Scripps Institution of Oceanography), ocean model development
N. Zabusky (University of Pittsburgh), """

Atmospheric Kinetics and Photochemistry (AKP) Project

H. Akimoto (National Institute for Environmental Studies, Tsukuba, Japan), joint research on ozone-alkene reactions
J. Bradshaw (Georgia Institute of Technology, Atlanta), NH₃ intercomparisons
J. Birks (University of Colorado, Boulder), reactions of ozone with carbon
D. Ehhalt (Institut für Chemie III, Kernforschungsanlage, Jülich, FRG), research on HO-H₂, HO-DH reactions
F. Fehsenfeld (NOAA Aeronomy Laboratory, Boulder), joint instrument comparison studies
H. Johnston (University of California, Berkeley), consultant on NₓOᵧ studies
A. Langford (NOAA Aeronomy Laboratory), Boulder NH₂ intercomparison
H. Niki (York University, Ontario, Canada), hydrocarbon intercomparison
D. Parrish (NOAA Aeronomy Laboratory, Boulder), NH₃ and hydrocarbon intercomparison
S. Penkett (University of East Anglia, England), hydrocarbon intercomparison
T. Quinn (University of Washington), NH₃ intercomparison
H. Schiff (York University, Ontario, Canada), NO₂ intercomparison
W. Seiler (Fraunhofer-Institut für Atmosphärische Umweltforschung, FRG), hydrocarbon intercomparison
H. Singh (NASA Ames), hydrocarbon intercomparison
W. Stockwell (State University of New York, Albany), simulation acid deposition

Atmospheric Odd Nitrogen Species (AON) Project

J. Anderson (Harvard University), collaboration on free radical experiments
E. Atlas (University of South Florida), examine photochemistry in remote Pacific troposphere
J. Dye (Mesoscale and Microscale Meteorology Division), odd nitrogen production from thunderstorms
F. Fehsenfeld, M. Buhr, M.A. Carroll, G Hübler, R. Norton (NOAA Aeronomy Lab), atmospheric measurements of organic and inorganic compounds
B. Heikes, B Huebert (University of Rhode Island), consultant on field experiments
W. Winn (New Mexico Institute of Mining and Technology), odd nitrogen production from thunderstorms

Atmospheric Chemistry of Aerosols (ACA) Project

J. Bottenheim (Atmospheric Environment Service, Ontario, Canada), arctic bromine and ozone interaction
D. Gillette (NOAA GMCC), alkaline dust flux estimation
A. Legge (University of Calgary), aerosol interaction with acidic pollutants
P. McMurry (University of Minnesota, Minneapolis), heterogeneous reaction mechanisms

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Global Observations and Modeling (GOM) Project

B. Boville (CGD), three-dimensional model interactions with data
G. Brassier (ACM), two- and three-dimensional model interactions with data
I. Hirota (University of Kyoto), satellite studies of middle-atmosphere dynamics
M. Hitchman (University of Wisconsin), satellite data applications
J. Holton (University of Washington), improved stratospheric observations
V. Kunde (Goddard Space Flight Center), analysis of stratospheric spectra
C. Leovy (University of Washington), improved stratospheric observations
M. Pirre (CNRS, Orleans, France), research with isentropic models
M. Shiotani (University of Kyoto), satellite studies of middle atmospheric dynamics
A. Smith (University of Michigan), satellite data applications
G. Visconti (University of l’Aquila), two-dimensional models
B. Wu (Chinese Academy of Sciences, People’s Republic of China), remote sensing
P. Zimmerman (BAC), UV effects on the biosphere

Optical Techniques (OT) Project

L. Heidt (BAC), airborne collection of air samples for trace gas distribution
P. Zimmerman (BAC), airborne collection of air samples for trace gas distribution and use of gas correlation radiometer
R. Cicerone (BAC), methane measurements with gas correlation radiometer
D. Griffith (University of Wollongong, Australia) development of emission spectroscopy for measuring trace gases in fire
J. Anderson (Harvard), studies of polar ozone
S. Solomon (NOAA), studies of polar ozone
J. Rodriguez (AER Corporation), studies of polar ozone
C.B. Farmer (Jet Propulsion Laboratory), studies of atmospheric infrared spectra
D. Murray (University of Denver), development of ground-based network
J. Margitan (Jet Propulsion Laboratory), studies of polar ozone
R. Watson (NASA headquarters), studies of polar ozone

Atmospheric Chemical Modeling (ACM) Section

R. Cicerone (BAC), chemical modeling
Climate and Global Dynamics Division (Climate Section), tracer-transport model development
L. Donner (University of Chicago), cloud convection scheme
J.-C. Gerard (University of Liege, Belgium), chemistry climate interactions
C. Granier (CNRS, Paris, France), multidimensional modeling of the middle atmosphere
M. Hitchman (University of Wisconsin), dynamics of the middle atmosphere
J. Kiehl (CGD), infrared cooling calculations; IR response to stratospheric perturbations
D. Moreau (University of Colorado/LASP), modeling of Martian atmosphere
J.-F. Muller (Belgian Fund for Scientific Research), modeling of tropospheric chemistry
M. Pirre (CNRS, Orleans, France), two-dimensional modeling in isentropic coordinates
K. Rose (Free University of Berlin, FRG), transport by planetary waves
A. de Rudder (Belgian Institute for Space Aeronomy), modeling of stratospheric ozone
M. Salby (University of Colorado), transport by planetary waves
A. Smith (University of Michigan), transport by planetary and gravity waves
S. Solomon (NOAA Aeronomy Laboratory), modeling of the middle atmosphere
F. Stordal (University of Oslo, Norway), stratospheric perturbation studies
J. Taylor (Australian National University), three-dimensional Lagrangian transport modeling

Biosphere-Atmosphere Interactions (BAI) Project

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DRAFT

D. Davis (Georgia Institute of Technology), hydrocarbon measurements
F. Fehsenfeld (NOAA Aeronomy Laboratories, Boulder), hydrocarbon measurements
J. Gosz (University of New Mexico, Albuquerque), terpene fluxes
D. Jonson (Colorado State University), methane emissions
D. Lowe (Institute of Nuclear Sciences, New Zealand), isotope measurements
H. Schiff (York University, Toronto, Canada), methane emissions
J. Taylor (Australian National University), methane emissions modeling
S. Verma (University of Nebraska, Lincoln), methane emissions
H. Westberg, Brian Lamb (LAR, Washington State University, Pullman), hydrocarbon flux studies
S. Wofsy (Harvard University), analytical instrumentation

In-situ Measurements Project

J. Anderson (Harvard University), trace gas measurements in the lower and middle stratosphere
R. Gammon (NOAA Pacific Marine Environment Laboratory), atmosphere and sea-surface trace gas measurements
D. Lowe (Institute of Nuclear Sciences, New Zealand), tropospheric sampling
W. Mankin (GRO), M. Coffey (GRO), P. Zimmerman (BAC), S. Tyler (BAC), G. Brasseur (ACM), and S. Madronich (ACTS), trace gas analysis
J. Peterson and R. Schnell (NOAA), field support for Trends in Atmospheric Constituents Study (TRACS)
M. Proffitt, K. Kelly, and D. Fahey (NOAA Aeronomy Laboratory), trace gas measurements in the lower and middle stratosphere
U. Schmidt and P. Roth (Institut für Atmospheric Chemistry, Kernforschungs Anlage, FRG),
A. Tuck (NOAA Aeronomy Laboratory), data correlations from the Antarctic and Arctic ozone experiments
R. Watson (NASA headquarters, Washington, DC), data correlations from the Antarctic and Arctic ozone experiments

Reactive Gases and Particles (RGP) Project

A. Johnson (University of Pennsylvania), cooperative bioatmospheric research
N. Schonbeck (Metropolitan State College), analytical methods development
R. Monson (University of Colorado), bioatmospheric research

Mesoscale Prediction Section

M. Biggerstaff (University of Washington), radar data analysis
P. Black (NOAA/AOML/HRD), hurricane rainbands
J. Chang (State University of New York, Albany), regional acid deposition modeling
W. Cotton (Colorado State University), retrieval of thermodynamic variables form Doppler radar data
D. Durran (University of Utah), mesoscale modeling and mountain wave research
K. Emanuel (Massachusetts Institute of Technology), tropical and extratropical cyclones; frontal dynamics
T. Gal-Chen (University of Oklahoma), dynamical meteorology
K. Gao (Hangzhou University), squall-line dynamics
J. Gyakum (McGill University), explosive cyclogenesis over land
R. Houze (University of Washington), EMEX and PRE-STORM analysis; MCSs over tropical oceans
D. Jorgensen (NOAA/WRP), mesoscale convective systems, PRE-STORM, and TAMEX
R. Kropfli (NOAA/WPL), downbursts and microbursts

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M. Larsen (Clemson University), use of wind and profiler data in mesoscale convective systems
D. Lilly (CIMMS, University of Oklahoma), mesoscale dynamics retrieval of thermodynamic variables from Doppler radar data
Y.-J. Lin (St. Louis University), analysis of Doppler radar data in TAMEX
B. Mapes (University of Washington), MCSs over tropical oceans
T. Matejka (NOAA/NSSL), retrieval of thermodynamic variables from Doppler radar data
M. Powell (NOAA/AOML/HRD), hurricane randbands
P. Ray (Florida State University), TAMEX data analysis
R. Reed (University of Washington), explosive cyclones
B. Ryan (CSIRO), retrieval of thermodynamic variables from Doppler radar data
T. Schlatter (NOAA/FSL), mesoscale data assimilation
N. Seaman (Pennsylvania State University), modeling of transport and dispersion of air pollutants
M. Shapiro (NOAA/WPL), explosive cyclones; dryline circulations
B. Smull (NOAA/WRP), squall-line dynamics
A. Thorpe (University of Reading), slant-wise convection; frontal dynamics
T.-C. Wang (National Central University, Taiwan), analysis of mesoscale data from TAMEX
R. Wakimoto (University of California, Los Angeles), microbursts; retrieval of thermodynamic variables from Doppler radar data
J. Weaver (NEDIS, Colorado State University), satellite data study of Denver convergence vorticity zone
J. Yoe (Clemson University), use of wind profiler data in mesoscale convective systems
G. Young (Pennsylvania State University), MCS interaction and EMEX analysis
D.-L. Ahang (University of Toronto), squall-line dynamics; mesoscale modeling

Convective Meteorology Section

T. Ackerman (Pennsylvania State University), comparison of cloud radiation model with aircraft data from FIRE
A. Arking (NASA Goddard Space Flight Center), validation of cirrus satellite retrieval methods
M. Baker (University of Washington), entrainment and mixing
V. Balaji (CNRM, Toulouse, France), cloud modeling
S. Barnes (NOAA/WRP), Denver geopotential height error
C. Beason (Lawrence Livermore National Laboratory), monotonic transport algorithms
R. Bleck (University of Miami), numerical techniques for ocean models
W. Blumen (University of Colorado), wave dynamics
R. Brady (NOAA/PROFS), convection initiation
C. Bretherton (University of Washington), convective dynamics
V. Bringi (Colorado State University), multiparameter radar
J. Brown (NOAA/WRP), mesoscale convective systems and Denver cyclone
R. Bruintjes (South African Weather Bureau), cloud modeling and ice physics
S. Cox (Colorado State University), derivation of cirrus cloud emissivities and ice-water content from Sabreliner measurements during FIRE
M. Decker (Cires, University of Colorado), Denver geopotential height error analysis
C. Doran (Battelle Pacific Northwest Laboratories), mountain/valley flow
J. Dudhia (Pennsylvania State University), mesoscale modeling and parameterization issues
D. Durran (University of Utah), mesoscale and modeling and mountain wave research
D. Farley (South Dakota School of Mines and Technology), cloud modeling
D. Fitzjarrald (State University of New York, Albany), numerical modeling of radiative fog
P. Flatau (Colorado State University), development of a three-dimensional model for cirrus clouds, including radiative feedback
A. Flossmann (University of Mainz, Germany), aerosol scavenging
R. Gall (University of Arizona), modeling fine-scale fronts
G. Grell (University of Miami), cumulus parameterization
T. Hauf (DFVLR, Germany), convection dynamics
J. Heldsdon (South Dakota School of Mines), electrification of clouds
K.-P. Hoinka (DFVLR, Germany), mountain wave drag
B. Heikes (University of Rhode Island), trace-gas fluxes in hurricanes
R. Houze (University of Washington), EMEX and PRE-STORM analysis; squall-line kinematics and momentum budget
J. Jensen (CSIRO, Melbourne, Australia), Hawaiian cloud band studies
D. Jorgensen (NOAA/NSSL), convective band structure in TAMEX
G. Klaassen (York University, Canada), instability at the cloud-environment interface
R. Knollenberg (Particle Measuring Systems, Inc.), analysis of anvil aircraft data taken during STEP
B. Kropfli (NOAA WPL), microbursts
J. Lafore (CNRM, Toulouse, France), initialization of cloud models using observational radar data
C. Lin (McGill University, Canada), explosive marine cyclogenesis
Y.-J. Lin (St. Louis University), analysis of Doppler radar data in TAMEX
K.-N. Liou (University of Utah), investigation of scattering properties of cirrus crystals
L. Margolin (Lawrence Livermore National Laboratory), monotonic transport algorithms
T. Mategka (NOAA NSSL), COPE squall line fluxes
M. Miller (ECMWF, England), convective gravity wave drag parameterization
H. Orville (South Dakota School of Mines), cloud physics
W. Petrier (University of Toronto, Canada), wave dynamics
H. Pruppacher (University of Mainz, Germany), aerosol scavenging
J. Redelsperger (CNRM, Toulouse), numerical modeling of squall lines
B. Reuter (McGill University, Canada), cloud modeling
A. Rodi (University of Wyoming), boundary-layer features related to convection initiation and downburst studies
S. Rutledge (Oregon State University), analysis of anvil data from PRE-STORM and squall-line kinematics
R. Srivastava (University of Chicago), radar analysis methods
D. Starr (State University of New York, Albany), interpretation of wind-field data in cirrus clouds during FIRE
R. Stewart (AES, Canada), explosive marine cyclogenesis
A. Tremblay (AES, Canada), explosive marine cyclogenesis
T. Wang (National Central University, Taiwan), TAMEX squall-line analysis
E. Westwater (NOAA/WPL), atmospheric profiler study
B. Wielicki (NASA Langley), cirrus cloud microphysics
D. Wolfe (NOAA/WPL), atmospheric profiler study
Q. Xu (CIMMS, University of Oklahoma), convective dynamics
P. Yau (McGill University, Canada), explosive marine cyclogenesis

Microscale Meteorology Section

M. Baker (University of Washington), entrainment and mixing
A. Blyth (New Mexico Institute of Mining and Technology), entrainment and cloud dynamics
V. Bringi (Colorado State University), radar differential reflectivity
R. Bruinjes (South African Weather Service), cirrus cloud studies
R. Cederwall (Lawrence Livermore National Laboratory), turbulence modeling
V. Chandrasekar (Colorado State University), radar differential reflectivity
H. Christian (NASA Marshall Space Flight Center), cloud electrification instrumentation
J. Curry (Purdue University), stratus-topped PBL
A. DeVries (University of Illinois), ice-crystal growth
J. Duman (Notre Dame University), protein antifreeze studies
R. Fall (University of Colorado), recrystallization of ice
R. Farley (South Dakota School of Mines and Technology), precipitation modeling

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G. Ferry (NASA Ames), polar stratospheric cloud measurements
J. Fishman (NASA Langley), turbulent flux measurements and trace species
A. Flossmann (Gutenberg University, Germany), aerosol and gas scavenging
P. Gallacher (NCAR Geophysical Turbulence Program visitor), turbulence
J. Glendening (Naval Postgraduate School), PBL modeling
G. Gregory (NASA Langley), turbulent flux measurements of ozone
R. Grossman (CIRES, University of Colorado), small-scale structure near the tropopause
B. Hicks (NOAA/ATDD), surface exchange of trace species
T. Horst (Battelle Pacific Northwest Laboratories), simulation of the stably stratified boundary layer
F. Hussain (University of Houston), vortex reconnection
N. Jensen (Risø National Laboratory, Denmark), flow over complex terrain
J. Jones (New Mexico Institute of Mining and Technology), cloud electrification
R. Kerr (NCAR Geophysical Turbulence Program visitor), turbulence
P. Kirkegaard (Risø National Laboratory, Denmark), turbulence modeling
R. Knollenberg (Particle Measuring Systems, Inc.), analysis of aircraft data taken during STEP
R. Kraichnan (Los Alamos National Laboratory), turbulence
L. Kristensen (Risø National Laboratory, Denmark), turbulence modeling
J. Latham (University of Manchester), electrification process
M. LeClerc (Utah State University), turbulent diffusion in canopies
R. Lee (Lawrence Livermore National Laboratory), pollutant dispersal
D. Lilly (University of Oklahoma), stably stratified turbulence
L. Mahrt (Oregon State University), stably stratified boundary layer
T. Marshall (University of Mississippi), particle-charge measurements
O. Métails (Grenoble, France), turbulence simulation
S. Orszag (Princeton University), turbulence simulation
M. Politovitch (NOAA), supersaturation in clouds
L. Poole (NASA Langley), polar stratospheric clouds
C. Popp (New Mexico Institute of Mining and Technology), chemical production from electrified clouds
H. Pruppacher (Gutenberg University, Germany), cloud microphysics and scavenging
D. Randall (Colorado State University), PBL parameterization
P. Ray (Florida State University), cloud electrification
J. Ritter (NASA Langley), turbulent flux measurements of trace species
K. Sassen (University of Utah), comparison of lidar and aircraft data from measurements in FIRE
C. Saunders (University of Manchester), thunderstorm electrification
D. Stedman (Denver Research Institute), turbulent flux measurements of trace species
R. Stull (University of Wisconsin), PBL modeling
P. Taylor (York University, Canada), PBL parameterization
J. Weil (CIRES, University of Colorado), air-quality modeling
W. Winn (New Mexico Institute of Mining and Technology), cloud electrification
W. Wu (University of Oklahoma), helicity
V. Yakhot (Princeton University), turbulent theory
S.-F. Zhang (University of Chicago), micrometeorology

Solar Interior Section

J. Christensen-Dalsgaard (Aarhus University, Denmark),
V. Dziembowski (Astronomical Center, Warsaw, Poland), research on p-mode inversino
P. Goode (New Jersey Institute of Technology), research on stellar structure, oscillations and magnetic fields
D. Gough (Cambridge University), research on solar oscillations, inverse theory, and stellar structure
W. Livingston (National Solar Observatory, Tucson), consultant on Fourier tachometer operations

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