1. Original proposal executive summary

The U. S. Department of Energy (DOE), through its CHAMMP initiative, hopes to develop the capability to make meaningful regional climate forecasts on time scales exceeding a decade, such capability to be based on numerical prediction type models. We propose research to contribute to each of the specific items enumerated in the CHAMMP announcement (Notice 91-3); i.e., to consider theoretical limits to prediction of climate and climate change on appropriate time scales, to develop new mathematical techniques to utilize massively parallel processors (MPP), to actually utilize MPPs as a research tool, and to develop improved representations of some processes essential to climate prediction.

In particular, our goals are to:

- Reconfigure the prediction equations such that the time iteration process can be compressed by use of MMP architecture, and to develop appropriate algorithms.
- Develop local subgrid scale models which can provide time and space dependent parameterization for a state-of-the-art climate model to minimize the scale resolution necessary for a climate model, and to utilize MPP capability to simultaneously integrate those subgrid models and their statistics.
- Capitalize on the MPP architecture to study the inherent ensemble nature of the climate problem. By careful choice of initial states, many realizations of the climate system can be determined concurrently and more realistic assessments of the climate prediction can be made in a realistic time frame.

To explore these initiatives, we will exploit all available computing technology, and in particular MPP machines. We anticipate that significant improvements in modeling of climate on the decadal and longer time scales for regional space scales will result from our efforts.
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2. Summary of accomplishments:

A. Model reconstruction efforts to speed up computations

A large segment of our community is now working on developing the techniques necessary to utilize massively parallel processors for solving the climate prediction problem by exploiting established numerical processes and state-of-the-art models. Nevertheless optimum use of current and near future MPPs using this approach may not meet the need for adequate computer processing time. This constraint is based on the fact that currently models are solved as a marching problem in time, and are thus limited in time by the number of steps needed to march into the future. Climate change requirements indicate that the prediction time be increased to the order of tens of years, with the added consequence that the impact of smaller scales must be assessed. Conventional wisdom suggests that to meet this goal model resolution must be increased, but this compounds the computational demand. Moreover, the interaction of the various coupling models defining physical and boundary processes also becomes yet more important, and each of these models requires more detailed calculations to assure the level of accuracy required. Since each of these models is represented as a marching problem it suffers the same computing limitations as the atmospheric model.

We have approached this issue from two perspectives. One is the possible reconstruction of the forecast system so that many time levels may be computed concurrently in a given machine cycle provided sufficient processors are available; this procedure has some commonality with increasing the integration time step, but distinct differences are inherent in the applications. The other technique involves using computing algorithms which optimize the properties of parallel processors.

We have exploited the latter procedure by applying the spectral representation with the barotropic vorticity equation (BVE) and then with a two level baroclinic model, a project supported in part by a NASA grant. Expanding in global functions (solid harmonics), integration of the BVE over the global surface yields a nonlinear set of first order coupled ordinary differential equations which can be extrapolated in time. Details of the development of these equations can be found in Baer (1964), and Baer and Platzman (1961) among others. The vector of expansion coefficients appears as differentiated in time and is evaluated as the sum of quadratic products of the coefficients themselves. The application to parallel processors becomes obvious when one notes that each quadratic product is
multiplied by a constant coefficient denoted as an interaction coefficient. If these coefficients are distributed to a processor, the quadratic products can be calculated concurrently for each expansion coefficient and the sum (or sweep) over all the processors yields the derivative field of the expansion coefficient vector. A suitable time stepping scheme then yields the new set of expansion coefficients. With a computer containing enough processors, this step can be accomplished in little over one machine cycle. Historically, this method for solving the prediction system proved unpopular because a technique denoted as the transform method, developed by Machenhauer and Rasmussen (1972) and Orszag (1970) was computationally more efficient on the available serial processors. In the environment of parallel processors, this judgement must be reevaluated.

The process although simple and straightforward has the drawback that as resolution increases the number of computations needed grows as the cube of the expansion coefficient index and thus becomes increasingly larger than the number needed to solve the problem by the transform method. If the number of processors were unlimited this difficulty would not exist, but clearly that will never be the case. The other difficulty arises from limitations in communication amongst the processors. At the end of each iteration, new values must be communicated to the processors so that they can produce a new product. Currently, this distribution process takes considerably more computer time than the actual product calculation in each processor and thus limits the benefits of parallel processing.

We have performed integrations with the BVE both in the interaction coefficient (IC) format and using the transform method for intercomparison purposes on the CM-5 at LANL. For various truncations the IC format has run as fast or faster than the transform method, despite the limitations of communication. This result has encouraged us to program and run some experiments with the baroclinic model, a model similar to the one used by Baer and Alyea (1971) and Alyea (1972). Preliminary integrations suggest that on the CM-5 the IC method is comparable to the transform method in speed. As communication amongst the processors improves, the speed advantage may shift to the IC method.

Our effort at reconstructing the prediction system to optimally use the parallel processors involves time compression. If we define the "computing cycle" to be that time required to do once all the calculations which must systematically be repeated to complete an entire calculation we would in principle attempt to do everything necessary in such a cycle. The longer the time step, the more
computations could be completed in one cycle. On a true serial machine which can handle just one computation at a time (non-vector), the computing cycle would be the time for that operation. On a massively parallel processor with unlimited processors, the computing cycle would include all the calculations which would not need repetition by their dependence on previous calculations. For conventional marching problems, the minimum computing cycle could be one complete time step. It is this computing cycle that we attempted to approach.

We demonstrated in our original proposal a procedure to extend the time step in a climate model, i.e., to calculate more than one time step in a computing cycle by noting that the equations we must solve represent an initial value problem and that the ultimate solution depends only on the initial conditions. Hypothetically it should be possible, by suitable restructuring of the numerical equations, to come to the final solution in only one computing cycle, achievable only with an unlimited number of processors. The example used was a first order linear differential equation with constant coefficients written in finite difference form. Repeated substitution shows that the solution at \( N \Delta \) can be represented as a function of the initial values which can be computed in one machine cycle on a parallel processor. This process clearly becomes complex when applied to a nonlinear system.

We concentrated on the simplest example to study the ramifications of time compression, the low order BVE. This model was first considered by Lorenz (1960) on the f-plane, and then by Baer (1970) on the sphere. We developed a formula by resubstitution to relate the variables at any time to the initial values which would allow a computation to be made in one machine cycle. However the number of calculations required grew astronomically as the time step grew large. The formula could also be represented by a Taylor Series and with a small error the number of terms was drastically reduced. Noting the formula for the low order system as follows:

\[
\frac{\partial \Psi_i}{\partial t} = a_i \Psi_j \Psi_k \ldots 1 \leq i, j, k \leq 3, \ldots i \neq j \neq k
\]

it can be seen that the terms for the Taylor Series can be developed by repeated differentiation of the system. This was accomplished by use of Mathematica (Wolfram, 1991). In addition this system has an analytic solution thereby allowing an accurate test of any numeric approximation.
The most interesting feature of this system involves the interaction of some planetary wave with a zonal current. A number of experiments were performed with different wavelengths, various shapes of the zonal current, different relative energy distributions between the wave and the zonal field and various amounts of total energy in the system. In each experiment, the number of terms of the Taylor Series required to give a good approximation to the exact solution was recorded.

Since we presume that all calculations for a given time step could be performed in one machine cycle for this simple system, we compared the solution by the Taylor Series method to the leapfrog scheme, requiring both methods to yield results within ten percent of the exact solution. We also tested the Taylor Series scheme using one sided and centered differences. Although there was considerable variability based on the initial conditions selected, the time step achievable with the Taylor Series was seven to ten times longer than the time step used for the leapfrog scheme. Although the Taylor Series method is bounded in time by the true oscillation period, that constraint was never met by any of our experiments.

Based on these positive results, the experiments were redone using the model on the sphere. Although the calculations were considerably more complex and involved many more computations, the results were comparable to those with the Lorenz model. The spherical model was then expanded to include two independent waves each with its own latitudinal structure and both interacting with an arbitrary zonal flow and comparable experiments were performed. Since this system does not necessarily have an exact solution it is more difficult to assess, and the analysis of its results is currently ongoing.

B. Subgrid scales, parameterization and closure

For climate scale prediction periods, higher model resolution in space is required to properly account for the effects of small scale activity on the scales of interest which currently are the regional climate scales. Unfortunately, Lorenz (1969) pointed out that small scale noise will propagate through the scale domain to the largest scales in a matter of a few weeks. Thus unless the ultimate solution is primarily dependent on forcing, and that the forcing overwhelms this error propagation, prospects for successful climate prediction are dim. Yet much of the forcing occurs on the small scales (for example convection) and must be properly assessed and incorporated into models.
Nonlinear models need some form of closure on space scales to allow integration to proceed. This is effected by subgrid scale parameterization and is done in a variety of ways, principally designed to avoid computational difficulties. Theoretical and computational studies with simplified flow systems such as those pioneered by Leith (1971) and Kraichnan (1967) have yielded valuable information regarding the statistical distribution of energy in the subgrid scales, and how this energy is propagated with time up and down the scale range. However, experiments with systems in high rotation such as the atmosphere and including significant external energy input over a broad scale range to include phenomena such as boundary layer friction and convection, indicate that incorporating time independent statistics for subgrid scale forcing is not adequate to provide successful predictions, in particular of the intermediate "regional" scales. Nevertheless scale truncation is essential.

We have approached this problem from two perspectives. On the one hand we have considered small scale impact on the larger scales by analysis of a simple model in which the closure problem stands in isolation and becomes prominent. Alternately, we investigate the resolution problem by studying the small scales independently of the global scales, intending to identify the principal forces which the subscale domain imposes on a global model and the time scales over which the subscale domain might be averaged.

1. Simple model studies

To understand if subgrid scale parameterization can be selected so that it is effective in the weather prediction problem as a forerunner to climate prediction, we focussed attention on parameterization of subgrid scale momentum flux in a spectral barotropic model. The model had options set to run without forcing, with topography and with a forcing function imposed in the baroclinically active wave domain to simulate baroclinic instability; see for example Basdevant, Legras, and Sadourny (1981). When this forcing was activated, a suitable viscosity was introduced to maintain energy conservation. The model had the option of triangular truncation at any scale and an eighth order linear dissipation function was imposed at the cutoff scale to establish realistic energy distribution in the shortest scales.

Several initial data sets were selected from the NMC archives and were run through the model until quasi-equilibrium between the zonal flow and the wave was established. Because the model without forcing does not tolerate standing waves,
this process was deemed necessary. Utilizing these processed initial fields, a number of experiments were performed.

Integrations were first made with no forcing for approximately fifteen days with the model truncated at T80 and results of those integrations were utilized as a reference; i.e., truncated versions of the integration with or without parameterization were compared to the reference calculations to assess the veracity of the parameterization in reproducing the reference results. Comparisons were focussed on the longer waves which contained the bulk of the energy.

A variety of parameterizations were attempted. Based on the results of turbulence theory [Stewart (1993), Branstator and Opsteegh (1989), Margolin and Jones, (1991), Jolly, Kevrekidis, and Titi, (1990), Germano et. al., (1990), Bernard and Handler, (1990), Lilly (1989), Zhou, Vahala, and Hossain, (1988), Leith and Kraichnan, (1972), Leith (1990), and Thompson (1973)], a fixed energy distribution in the subgrid scales taken from sample integrations with the reference model and which approximated a -3 spectrum was first attempted. This was imposed in the range 64 ≤ n ≤ 80. Other truncations were also run. Since the statistical theory does not impose a constant on phase, the experiments were rerun with the fixed amplitude spectrum, but with random phase. To test other possible parameterizations, regression formulae were developed from test model runs relating to subgrid scales both to the tendencies of the long waves and independently to the shear of the zonal current. Finally, both amplitude and phase in the subgrid range were imposed based on random numbers, but numbers chosen smoothly and constrained about mean values in time. Integrations for the variousinitial states were run with each of the separate parameterizations and for a variety of truncations, the lowest at T31 and the highest at T80. In addition, integrations were performed with no forcing, with topography only and with both topography and simulated forcing as described above.

The results from these experiments were singularly uniform. By and large, the ability of the models with parameterization to reproduce the long waves as defined by the reference model degraded seriously in ten days. As resolution was increased, the rate of decay was slowed, but not stopped. This result was observed for each parameterization scheme. When topography alone was introduced, the rate of degradation increased, whereas when heating was introduced, the period of accurate forecast was increased. This result was anticipated, since we expect that forcing on the active scales might overwhelm the subgrid parameterization (also a
form of forcing). Indeed, when the forcing was centered on the smallest scales in the model to simulate the effects of convection, the parameterized models deviated most rapidly from the reference, indicating the strong impact of the short scales on prediction quality.

Two tests whose results stand out are the following: if the models with parameterization were run at the reduced cutoff scale but without the parameterization, the results were comparable to those with parameterization. Additionally, if the reference model was run with the initial data in the subgrid domain of a reduced resolution model set to zero, the results of the integration were very similar to the reference model results, indicating that the initial distribution in the subgrid domain was of little consequence but its nonlinear involvement in the total system was essential and could not be easily parameterized.

The significance of these results are related to the possible negative prediction potential of regional climate, which involves the smaller space scales and on shorter time scales. We note however that the experiments presented are based on a substantially simplified model and do not involve real forces of the magnitude imposed by say, the oceans.

Several integrations were then performed to sample the effects of parameterization on the climate time scale. Runs were made for 1000 days with the T63, T42 and T31 truncations to test the sensitivity to resolution. Without topography or forcing, 99 percent of the initial energy drifted into waves $n \leq 10$, and the climatic characteristics of the various truncations were very similar, showing low frequency oscillations in the range of ten through fifty days. These efforts are ongoing and will be discussed under future plans.

2. Subgrids and GCMs

To understand the resolution problem, small scales can be studied independently of the global scales. We attempt to identify the principal forces which the subscale domain imposes on the global model and the time scales over which the subscale domain might be averaged. Since the subgrid scale domain is locally space dependent, we identify domains which are sufficiently homogeneous to be included in any one model and develop a set of such regionally dependent models, and because high frequency motions are predominant, we also consider nonhydrostatic effects. We identify the time periods over which each of these local models can provide useful forcing for a global model truncated at a less fine scale resolution.
A scenario for application of this approach is the following. A global climate model of the atmosphere with its associated interactive models is developed and truncated at a reasonable scale to include meaningful regional climate areas. A set of subregional models is simultaneously developed to encompass spatial scales not included in the global model. These models include the uniqueness and hopefully the homogeneity of the local region they represent, and their number in sum covers the entire space of the domain of the global model. The appropriate properties relevant to the subregion models are included in each and their properties are predicted over their domain for the time scale identified as appropriate to each. The time statistics of these predictions are utilized in the global model for closure purposes; note that these closure statistics are by definition both space and time dependent. The subscale models can all be calculated during the same computing cycles on a MPP, provided adequate processors are available. The procedure filters out unwanted small scale noise and yet provides realistic forcing to the primary model on all scales.

All GCMs contain subgrid parameterizations to model a substantial amount of physical processes. In most spectral models, grid point parameterized physics are performed on the grid used by the spectral transform which computes an alias free quadratic product in the resolved spectral domain. However, this grid was designed solely for computing quadratic nonlinear terms coming from dynamics and it has significantly more degrees of freedom than the corresponding spectral truncation. Very little is known about how the climate of spectral models depends on both the resolution and type of grid used for subgrid parameterizations. We have seen in the CCM2 that forcing due to subgrid scale processes is quite different even at very high resolutions.

To investigate this question of dynamics resolution vs. physical parameterization resolution further, we are developing a version of the CCM2 in which the parameterization and dynamics can be performed on separate grids. To date, we have divided the dynamics and physics into two separate components. Communication between these components is in spectral space. The physical parameterizations provide spectral coefficients of tendencies of temperature and momentum which are added to the state variables. The physical parameterizations are driven by the state variables reconstituted on the parameterization grid after the dynamical forecast. Thus, the mapping between different resolutions will occur in the spectral domain. The semi-Lagrangian water vapor transport is associated
with the physical parameterization component and remains in grid space. Currently the dynamics and physical parameterization components have the same resolution. We have examined the impact of the restructuring on the simulations. During the remainder of the current contract we will add the additional generality to run the dynamics on a different resolution than the physics parameterization. Thus we will be positioned to examine the impact of different parameterization scales on simulation capability as described in the next section.

This work has also lead us to a study of spectral transform algorithms using grids other than the usual Gaussian latitude-longitude grid. We have shown that for any triangular spectral truncation, there does not exist a quadrature based transform which uses a grid with the same number of degrees of freedom in the spectral truncation (Taylor, 1994). However, we have developed medium to high resolution spectral transforms (up to T213) for such minimal grids by using matrix factorization instead of quadrature. These minimal grid transforms are competitive in speed and accuracy with the quadrature transform and have substantially fewer points. They are similar to the reduced grid used by the ECMWF, but provide a larger reduction in the number of points and a more mathematically rigorous justification. It appears that such a minimal one-to-one grid is ideally suited to the manner in which subgrid physical parameterizations are conceived as grid cell averaged tendencies. This grid is of necessity suited for implementation with a semi-Lagrangian advection scheme which does not require an alias free computation of the quadratic terms. This combination will be pursued in conjunction with the group at NCAR investigating numerical algorithms under the auspices of CHAMMP.

C. Distributed climate ensemble studies

The inherent ensemble nature of the climate problem and the manner in which this may be capitalized upon using machines with massively parallel architecture is our focus. Traditionally the climate ensemble is generated in general circulation models by mimicking the generation of climate realizations in the physical climate system, i.e. the sequential generation of daily weather from long integrations through many seasonal cycles leading to an ensemble of realizations of particular months, seasons and years. The climatic mean of any particular time period is then the arithmetic average of the ensemble of realizations of this time period contained in the long, sequential integration. Natural climate
variability is the deviation from the climate mean of the realizations of the time period within the climate ensemble. Massively parallel architecture allows us to circumvent the generation of the ensemble elements of the climate distribution by integrating in parallel a number of members of the climate ensemble. For example, if N is the total number of processors and a model of the climate system can be efficiently integrated on a subset K of the processors, then L = N/K realizations of a year of climate data can be generated simultaneously from judiciously chosen initial states. Each subsequent year of simulation results in L additional realizations of a year of the climate ensemble.

To realize this L-fold economy of generation of ensemble members two issues must be addressed. The first of these is the problem of the optimal number of processors (K) upon which each ensemble member of the climate system is integrated. If it is assumed that a state-of-the-art model of the climate system will be programmed to occupy all of the N processors of an MPP machine in the integration of a single realization of the climate ensemble as in the traditional approach outlined above, then the parallel computation of L ensemble members will only be useful for studies involving the integration of lower-resolution/simpler models of the climate system. Such studies are almost always necessary to better understand the meaning and sensitivity of the results of the state-of-the-art models and for exploratory research into the interactions of the various components of the climate system. Additionally, it is not clear that the assumption made above will remain true indefinitely into the future. Because of the rapid advances being made in chip technology and MPP computing capability, it is not out of the question that in the future more than a single realization of the climate ensemble will be simulated simultaneously within a MPP even with the most advanced climate system models. This is due to the trade-off between arithmetic speed at each processor and inter-processor communication speed. A single realization computation must rely on rapid communication between all N processors, while a computation of L realizations needs communication between K = N/L processors. Thus the ratio of communication speed to arithmetic speed can be smaller in a problem which has L-fold independence.

"Judicious choice" of initial states alluded to above is addressed by constructing them using the most important modes of climate variability. This approach guarantees the independence of the ensemble elements as they evolve in time and samples different portions of the climatic probability distribution. When
dealing with the atmospheric component of the climate system the identification of
the most important modes of climate variability is not a difficult task because of the
relatively long observational record and the substantial experience already gained
in atmospheric general circulation modelling. However, for the coupled systems
representing interannual to decadal scale climate variations very little is currently
known about the modes of variability, and we therefore analyze such variability in
lower-resolution/simpler coupled climate system models.

As should be clear from the above, the efficient generation of climate
ensembles is not the sole application of distributing different realizations of the
climate ensemble on subsets of processors of a MPP machine for computation. An
immediate application of this technique can be in parameter sensitivity studies
which gauge the uncertainty of our ability to faithfully simulate and project the
future climate changes due to increasing concentrations of greenhouse gases. As
mentioned above, current subgrid scale parameterizations are among the most
uncertain aspects of present day climate models, which is one of our rationales for
explicitly modeling these terms rather than using standard parameterizations. Our
explicit modeling studies will not only give an alternative to parameterization but
will also allow us to calibrate the range of parametric values used in current
parameterization schemes. We intend to use this range of values to determine the
uncertainty inherent in climate simulations by integrating an ensemble of climate
system models. This ensemble of sensitivity studies will be most efficiently
integrated using the distributed technique described above.

Lastly, our distributed technique will be an efficient method of studying the
problem of climate determinism in climate system models which involve the deep
ocean circulation. As recently pointed out by Bryan (1986), the coupled ocean-
atmosphere system may be one with multiple equilibrium solutions corresponding
to the presence/absence of interhemispheric thermohaline circulations in the ocean.
The existence of multiple climatic equilibria (or climate intransitivity in the
nomenclature of Lorenz, 1964) is nearly impossible to ascertain using the
traditional method of climate ensemble generation. Because the particular climatic
equilibrium attained in any climate simulation is initial state dependent, if the
climatic statistics are intransitive, the only way in which this problem can be studied
is by using the ensemble approach which is most efficiently computed using the
distributed method described above.
Since none of the applications of the distributed ensemble approach necessitate the use of state-of-the-art climate system models (even the climate determinism/intransitivity questions can be studied in simple models, Bryan, loc. cit.), we also study this technique using simple nonlinear models of the climate system. This allows us to gain experience using the distributed technique while permitting the state of massively parallel architecture machines to develop to the stage where more advanced and higher resolution models will be able to take full advantage of this method.

As a precursor to studying the potential for concurrent generation of climate ensemble statistics using state of the art climate models, we have developed the following capacity with simpler climate models:

- We have developed a global linear balance atmospheric model.
- We have implemented Lorenz' (1984) hydrologic cycle.
- We have coupled this model to a simple ocean model, a generalization of that developed by Kallen and Huang, (1986).

This simple and fast model allows us to make very long runs to study the degree of intransitivity in the climate generated by the existence of multiple steady thermohaline circulations.

We are also using this model to develop the technique of applying EOF's to initialize multiple runs, thus allowing the exploration of the phase space of the model and the production of very long time statistics in an efficient way on parallel computers.

A key concept is to find an optimal way of exploring the phase space of a climate system. Since the time integrations of two very close initial states diverge rapidly, there may be a way of choosing a set of "interesting" initial states such that their time integrations will produce a "richer" exploration of the phase space than the time integration of any single initial state for an equivalent global integration time.

Our currently explored strategy can be described as follows:

1. We integrate a number N of initial conditions for a time T;
2. For all generated realizations, we compute the Empirical Orthogonal Functions (EOF);
3. We project on these EOFs all the realizations in phase space;
(4) The extrema of these projections provide for the extent of the smallest rectangular box "B" containing all the generated realizations (the extrema of these projections are actually the center of the faces of B);

(5) We use the center of edges (or the summits) of B as a set of new initial conditions;

(6) We restart at point 1.

This strategy should shorten the global integration time required for EOF stabilization (this is actually the criterion we intend to use to determine if a time integration has been carried on long enough). The strategy is almost completely implemented on the Lorenz system of equations and seems to prove effective in that context.

The implementation of a baroclinic two level atmospheric model is now underway. Considerable difficulties were encountered during the port of this model to the CM-5 parallel computer. Recent results lead us believe that we will obtain comparable performance to a Cray YMP/8 with a CM-5 32 node machine. Complete rewriting of the code has been required to achieve this level of performance.

Finally, a careful examination of the projections of the phase space onto the EOFs should allow us to describe the possibly existing Markov chain of a climate system by locating transitions between quasi-stable climate states.

3. ADDITIONAL ACCOMPLISHMENTS

A. Collaborative efforts

Francois Thibaud has created, organized and animated NCAR's CM-5 User's Group. In his capacity as leader of that effort, he was involved in shaping the emerging International Connection Machine User's Group (ICMUG) with people from ACL/LANL, NAS/NASA and NCAR. When operational, this User's Group should give great service to the users community by providing a forum to discuss parallel computing issues and ease communication with TMC.

Rich Loft, Thinking Machines' representative at NCAR, assisted us in software porting to the CM-5 by developing a toolkit to ensure that maximum possible efficiency is attained.

R. Saravanan, an NCAR CGD Scientist I, has assisted us in the development and diagnosis of simplified climate models at no cost to the project.
Professor Baer was a Co-PI on an ARM grant and in that capacity maintained and helped develop interaction between the ARM and CHAMMP programs.

Dr. Williamson was a member of another CHAMMP collaboration involving NCAR, ORNL and ANL which developed reduced grid and semi-Lagrangian versions of the CCM2, and implemented them on MPP platforms.

B. Attendance, participation and presentations at meetings and workshops

- **Ferdinand Baer**
  - DOE Shallow Water Conf., Oct. 91, Boulder, CO
  - Presentation: Interaction coefficient methodology on MPPs.
  - AMS/NWP Conf., Oct. 91, Denver, CO
  - Presentation: Model scaling.
  - CHAMMP STM, Mar. 92, Las Vegas, NV
  - Presentation: Progress report on CHAMMP grant.
  - CAS92, June 92, Santa Fe, NM
  - Lecture, Stockholm Univ., Aug. 92, Stockholm, Sweden; Discussed progress on CHAMMP grant.
  - Lecture, Swedish Meteor. and Hydro. Institute, Sept. 92, Norrkoping, Sweden; Discussed progress on CHAMMP grant.
  - Lecture, Danish Meteorological Institute, Sept. 92, Copenhagen, Denmark; Discussed progress on CHAMMP grant.
  - International Conf. on Global Modeling, Sept. 92, Hamburg, Germany.
  - PCMDI/AMIP meeting, Nov. 92, Livermore, CA; Discussed CHAMMP project activities.
  - AMS Annual meeting, Jan. 93, Anaheim, CA.
  - CHAMMP Wkshop on Alternatives to GCMs, Feb 93, Oakland, CA.
  - CHAMMP STM, Mar. 93, Monterey, CA;
  - Presentation: Progress report on CHAMMP grant.
  - NOCLIMP/EUCREX workshop, May 93, Stockholm, Sweden; discussed CHAMMP project modeling efforts.
  - Lecture, Swedish Meteor. and Hydro. Institute, May. 93, Norrkoping, Sweden; Discussed continuing progress on CHAMMP grant.
  - Community Climate Model Wkshop, June 93, Boulder, CO.
  - IAMAP Symposium, July 93, Yokohama, Japan.
  - ARM/CHAMMP Wkshop, Sept 93, Ft. Collins, CO
  - Presentation: Interactions of ARM and CHAMMP programs at UMCP.
  - Climate Diagnostics Workshop, Nov. 93, Boulder, CO; Discussed CHAMMP modeling efforts.
  - AMS Annual meeting, Jan. 94, Nashville, TN.

- **Joseph J Tribbia**
  - CHAMMP STM, Mar. 92, Las Vegas, NV;
  - Presentation: Progress report on Exploitation of Parallelism in Climate Modeling.
  - CHAMMP workshop on Alternatives to GCMs in Climate Modeling, Feb. 93, Berkeley, CA.
David L. Williamson

-- CHAMMP Directed Team Meeting, Santa Fe, NM, April 3, 1992.
Presentation: Simulations with a semi-Lagrangian Version of CCM2.
Presentation: Proposed test cases for numerical approximations to the shallow water equations in spherical geometry.
Presentation: The semi-Lagrangian version of the NCAR CCM2.
Presentation: Climate simulations with a semi-Lagrangian version of the NCAR CCM2.

Mark Taylor

-- CHAMMP STM, Mar. 93, Monterey, CA.
-- AMS Annual meeting, Jan. 94, Nashville, TN;
Presentation: "Investigations of climate predictability".

Francois Thibaud

-- CHAMMP STM, Mar. 93, Monterey, CA.
-- AMS Annual meeting, Jan. 94, Nashville, TN;
Presentation: "Investigations of climate predictability".

C. Subgroup science team meetings

The subgroup science team which plans and carries out research on our CHAMMP grant, consisting of Baer, Tribbia, Williamson, Taylor and Thibaud as members, met on the following occasions to discuss the project: July, 92, UMCP; Oct. 92, NCAR; Jan. 93, NCAR; July 93, NCAR; and OCT. 93, NCAR.

D. Publications
1. Time compression studies:
Mr. Bing Zhang, a graduate student in the Department of Meteorology at the UMCP worked on this project. He received a MS degree from the University in 1993 with support from our CHAMMP grant and wrote a scholarly paper with the
Use of Taylor Expansion in Computation of the Simple Spectral Barotropic Vorticity Equation*

Bing Zhang
Department of Meteorology
University of Maryland College Park

ABSTRACT

Time integration is the basic part of the computation of meteorological forecast models, but the time step is constrained by stability consideration, CFL condition must be satisfied for linear problems. The time steps are very short for high frequency components, this makes the integration procedures extremely time- consuming, especially for climate models. The current popular numerical integration scheme for time integration is three time-level leapfrog scheme which uses the first order derivative at the mid-level, we will refer this method as the regular leapfrog scheme. In this paper, a system of the simplest spectral barotropic vorticity equation in channel domain is experimentally computed by using Taylor's expansions of time dependent variables so that higher derivatives are included in computing the values at next time level. Taylor's expansion is applied for two computational schemes: one is "leapfrog" with the derivatives evaluated at the mid-level, the other is the two time-level forward scheme with the derivatives evaluated at level one, at which all variables values are considered as known, and the predicted outputs are given at level two. The experiment shows that on the average, when certain number of derivatives are included in the expansions, the integration time step can be more than 6 times of those given by the regular leapfrog scheme without losing any accuracy. This results tells us that it is possible to integrate the equations with a much higher time step by rewriting the forecasting equations in their Taylor's expansion forms. Although Taylor's expansion forms are usually much more complicated compared with the forms of the regular leapfrog scheme, time integration can still be fastened if each term in Taylor's expansion is assigned to one processor of the Massive Parallel Processors. The deal is the lose of simple expression form in exchange of the gaining of computational speed when MPP is used. In addition, the simple expansion form of the regular leapfrog scheme (several integration time steps are combined into one expression) is tested. Compared with Taylor's expansion forms, it will take about two orders magnitude higher computation times for the same increase of integration time step. This shows that the perspective of making use of Massive Parallel Processors with the use of Taylor's expansion forms are brighter.

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2. Subgrid scales, parameterization and closure (Simple model studies):

Mr. Eric DeWeaver, a graduate student in the Department of Meteorology at the UMCP worked on this project. He received a MS degree from the University in 1994 with support from our CHAMMP grant and wrote a scholarly paper with the following title and abstract.
On the Dynamics of Extratropical Low-Frequency Atmospheric Variability*

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ABSTRACT

The discovery of El Nino/Southern Oscillation (ENSO) as a dominant mode of interannual variability has lead to considerable optimism that circulation anomalies on seasonal timescales can be predicted. On the other hand, many studies have shown that extratropical low-frequency variability is maintained by the convergence of momentum flux by synoptic-scale eddies. Further analysis shows that high-frequency eddies are organized and controlled by the low-frequency flow. If the low-frequency flow does exert a dominant influence on the high-frequency eddies, it may be possible to construct a model in which the high-frequencies are parameterized in terms of the predicted low-frequency flow. Low-frequency flow anomalies would then be directly attributable to slowly varying boundary forcing and strictly low-frequency dynamics. This research is intended as a contribution to the goal of constructing such a model.

While our ultimate goal is to design a general low-frequency model, we have focused on the specific case of seasonal streamfunction anomalies associated with tropical heating events. To examine these anomalies, we have constructed a steady-state barotropic diagnostic model. The model simulates the streamfunction anomaly between two seasons at a given level using the observed fields of divergence and transient vorticity flux convergence for the two seasons. Because the basic state of the model is the average of the flow for the two seasons, the model is automatically linear. Thus the global streamfunction anomaly can be thought of as the linear sum of the streamfunction anomalies forced from various regions by various processes.

*This work is supported by the U. S. Department of Energy; Office of Energy Research; Special Research Grant: CHAMMP, grant number DE-FG05-91-ER61219.

3. Subgrids and GCMs:

The following two manuscripts relate research needed for the implementation of process models into global models for the purpose of subgrid parameterization. The first relates to the use of process models submitted to *Monthly Weather Review*. The second relates to the computational framework needed for the global model and submitted to *Journal of Computational Physics*.

An Alternative Approach to a Description of the Atmospheric Convective Boundary Layer

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ABSTRACT

The data base from Cloud-resolving Numerical Model is analyzed. It is shown that characteristic scale of convective flows is about a cell-size, and it may be orders of
magnitude larger than the integral scale of any flow parameter. It is demonstrated that all characteristics of atmospheric convective flows estimated by averaging over the length about 25---250-km (which is typical for observations) are random values, and they may vary over a wide range. It is suggested that such short-length average characteristics should be described by their sampling probability distributions rather than the ensemble averages. It is demonstrated that such distributions can be obtained from numerical experiments, and they may be used for comparison of numerical experiments with observations as well as for parameterization of GCMs.

*J. Tribbia's contribution to this work is being supported by the U. S. Department of Energy; Office of Energy Research; Special Research Grant: CHAMMP, grant number DE-FG05-91-ER61219.

Shallow Water Test Case Solutions Using Spectral Elements in Spherical Geometry*

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ABSTRACT

The success of the spectral element method in ocean modeling has prompted the consideration of its use in global climate modeling. The first step used in evaluating the suitability of spectral elements for climate modeling is the implementation of the method in spherical geometry and measurement of its performance relative to other methods with a battery of numerical simulations. For this purpose, the now standard suite of shallow water test cases proposed by Williamson et. al. (1992) is adopted. The results presented show that the spectral element method is significantly more accurate than standard finite difference models in terms of accuracy at comparable resolution. It is however shown that it is possible to achieve competitive accuracy with a modest increase in resolution. It is also shown that for fixed number of elements the spectral element model displays exponential convergence with increasing resolution.

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We have recently begun to explore the Spectral Element Method as a device for conveniently segmenting the global domain so that we may investigate the applicability of parallel processing in subgrid scale parameterization Mark Taylor is leading this effort and has presented the following papers:


Mark has collaborated and published two additional papers on the subject with support from our project, one published in *SIAM J. Numer. Anal.* and the other submitted to *Atmosphere-Ocean.* Abstracts of these papers follow.

**Cubature for the Sphere and the Discrete Spherical Harmonic Transform**

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**ABSTRACT**

Using a result of Bannai and Damerell, it is shown that a cubature formula with \( N \) points of degree \( 2s > 4 \) for the surface of the \( n \)-dimensional sphere \( U_n \) cannot achieve the classical lower bound of \( \dim P^s \), where \( P^s \) is the space of all polynomials in \( n \) variables of at most degree \( s \) restricted to \( U_n \). This implies that for \( n > 2 \) there does not exist a cubature-based discrete \( n \)-dimensional spherical harmonic transform for degree \( s > 2 \) with the same number of points as spectral coefficients.


**Global Modeling of the Ocean and Atmosphere Using the Spectral Element Method**

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Rutgers University  
and  
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**ABSTRACT**

The use of spectral methods now has a long history in global atmospheric modeling wherein the attractive properties of Fourier series on spheres, including higher-order convergence rates and efficient implementation via the transform method, have proven advantageous. Partially offsetting these advantages, however, are several competing disadvantages. Two of these, the appearance of Gibbs oscillations for localized processes (e.g., orographic interactions) and the difficulty of mapping spectral techniques onto parallel computer architectures, are inherent to the global nature of these techniques. A third drawback, the restrictions of these methods to regular geometries, has severely...
limited their application to the modeling of the large-scale ocean circulation.

We describe a global circulation model that has, in principle, none of these limitations. The model utilizes the spectral element method that combines the geometrical flexibility of traditional finite element methods with the rapid convergence rates of spectral approximation techniques. Simple test problems drawn from both oceanic and atmospheric modeling is exponentially convergent, yet allows effective representation of irregular geometry and efficient grid refinement in regions of dynamical interest. Lastly, performance characteristics on the nCUBE/2 and Cray T3D architectures confirm that the element model is ideally suited to the parallel computing environment.

REFERENCES


