Final Report

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Title:
Exploitation of Parallelism in Climate Models

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ORIGINAL EXECUTIVE SUMMARY

The U. S. Department of Energy (DOE), through its CHAMMP initiative, planned 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 proposed research to contribute to each of the specific items enumerated in the original 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 were 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 exploited 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.

I. Introduction

Our plan for the grant was outlined by three primary initiatives enunciated above; (a) to reconfigure the atmospheric prediction equations such that the time iteration process could be compressed by use of MPP architecture; (b) to develop

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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; and (c) to capitalize on the MPP architecture to study the inherent ensemble nature of the climate problem. Our approach gradually coalesced on dealing with regional and global climate modeling concurrently from two different model perspectives, always considering the use of MPPs as the principal tool. During the reporting period under consideration, we pursued the following initiatives:

- parallel algorithms with spectral accuracy;
- concurrent climate simulations;
- model reconstruction efforts to speed up computations;
- optimum realization statistics;
- parameterization studies;
- The impact of subgrid scale motions and their parameterization in atmospheric models.

II. Accomplishments

A) Parallel algorithms with spectral accuracy

Our interest in developing time and space dependent sub-grid parametrizations, as well as our interest in studying the resolution sensitivity of sub-grid parametrizations lead us to develop a spectral element atmospheric model. This is a type of finite element method in which a high order spectral function is used within each element. The method provides spectral accuracy while retaining both the parallel efficiency and geometric flexibility of unstructured finite elements grids. This geometric flexibility makes the model an ideal tool for studying sub-grid parametrizations, since regional or sub-grid scale resolution can be achieved (over a limited region) within a global model in a truly interactive way.

We first developed an MPP spectral element shallow water model for the sphere, based on the Rutgers oceanic spectral element code (Iskandarani et al., 1995). We then made use of the now standard shallow water test cases for the sphere (Williamson et. al., 1992) to verify several points:

1) The spectral accuracy of the method, even for the difficult non-linear test cases in spherical geometry;

The shallow water test cases allowed us to compare the spectral element method with several other methods without having to obtain and run the other codes. The test cases prescribe several forms of error and how they are to be computed so that any method can be compared objectively to several other methods by simply consulting the literature. The results were as expected: On a per-grid point basis, our method achieves error levels similar to that of spherical harmonic spectral methods, and significantly more accurate than finite difference methods. The results also show the spectral element method has no problems with spherical geometry. This is due to the fact that the sphere can be tiled almost uniformly with quadrilateral elements. This work was described in Taylor et al, (1997), and Haidvogel et al, (1997).

2) The almost perfect parallel efficiency and scalability of the method;

The spectral element method is ideal for MPPs. The spectral elements are distributed equally among the processors. Communication costs are minimal since each element needs only to communicate its boundary data with neighboring elements. The computationally intensive spectral transforms that must be performed within each element are localized to each processor and require no communication. On the Cray T3D, for a wide variety of problem and machine sizes, the parallel efficiency of the algorithm never drops below 95%. By this we mean that the time spent on inter-process communication is never more than 5% of the total, resulting in almost perfect parallel scalability. Furthermore, the method is well suited for the latest generation of supercomputers utilizing cache-based microprocessors. These computers work best with well "blocked" codes, where lots of computations are performed on small blocks of data that fit into the cache of the processor. The elements in the spectral element method provide a natural way to block the code. Unlike spherical harmonic spectral methods, the size of these blocks in the spectral element method is small and independent of resolution. Thus we have good performance even at resolutions above T85 where global spectral models start to experience cache "thrashing".

3) The effectiveness of the localized mesh refinement capability of the method;

Finally we used the test cases to show that the local mesh refinement capability of the method is quite effective. It improves the solution within the region of high resolution without degrading (and sometimes improving) the solution over the rest of the sphere. We then created a more extreme test by increasing the steepness of the topography in the flow past a mountain test case. With uniform spectral element grids, severe Gibbs type oscillations appeared upstream of the mountain that were only removed at T360 and higher resolution. However, results as good as the T360 results could be obtained using a spectral element grid with T42 resolution over most of the sphere and a 10-fold increase in resolution near the mountain. This run was 10 times faster than the T360 uniform resolution run.

The success of the spectral element method with the shallow water equations has prompted us to develop a primitive equation version of the model (SEAM, for Spectral Element Atmospheric Model). We have completed this work, making extensive use of the Held-Suarez test cases (Held and Suarez, 1994) to validate SEAM and compare SEAM with other GCM dynamical cores. The results are practically identical to Held-Suarez results from their spherical harmonic spectral model. SEAM also performs well. Results at T42/L20 resolution on 64 nodes of the Cray T3D show that SEAM runs about 9 times faster then the dynamical core from NCAR's CCM3. At present SEAM uses an explicit time step 8 times smaller than CCM3, so much of this gain is lost. However, we have demonstrated, to be reported later, that we can increase this timestep by at least a factor of three.

B. Concurrent climate simulations

We undertook a number of experiments in support of our study of the utility of ensemble methods in understanding the climate dynamics of models of the earth system which exhibit almost intransitive behavior. In association with our studies involving thermohaline reversals as examples of such bimodal systems, we pursued a simpler atmospheric example of multiple jet structure and equatorial super-rotation as described in Saravanan (1993). The atmospheric dynamics of this example involved the balance between eddy forcing and zonal jet structure. Because only the atmosphere is involved, climate statistics equilibrate much more rapidly than in the coupled system and, thus, this is an example of a more rapidly evolving climate distribution. This example, which is believed to be relevant for the equatorial dynamics of the equable climate of 6000 y BP, served to demonstrate the efficacy of this technique even for atmosphere alone climate studies and is a precursor to the examination of an interesting paleo-climatic period of reduced ENSO variability.

We were in the final stages of computational experiments investigating the boundaries of the basins of attraction for each of the two meta-stable climate states. In addition to this demarcation we were examining the dependence of residence time within the super-rotation state upon proximity to the basin boundary. This work on the concurrent simulation of multiple climate regimes will be completed during the continuation of the current grant.

Planetary wave bimodality was also studied in the NCAR CCM and reported on by Tribbia at the Wiin-Nielsen Symposium (Tribbia 1995, abstract only). To further investigate these and the above mentioned atmosphere alone questions in a more realistic modeling context, an R15 version of CCM2 was tested in an ensemble mode on the Cray T3D at NCAR.

An extension of the work to design efficient methods of probabilistic predictions of planetary wave regime transitions was underway at the grant's conclusion. (This work was reported upon at the University of Wisconsin, the AGU Fall meeting and the SIAM meeting on mathematical methods in the geosciences.) The problem of planetary wave regime transitions is an atmosphere only manifestation of the type of predictability problem which arises in climate prediction- the necessity of specifying the likelihood of remaining in the current (meta-stable) regime and the probability of transiting to one (or more) meta-stable state(s). On decadal to centennial time scales such regimes are associated with midlatitude- tropical ocean interactions involving ENSO and possibly oceanic Rossby waves and/or subtropical subduction in the Pacific and with variations in the North Atlantic involving thermolhaline circulation variations, sea ice fluctuations and air-sea interaction with atmospheric teleconnection patterns.

C. Model reconstruction efforts to speed up computations

Currently climate prediction models are solved as a marching problem in time, and are limited in time by the number of steps needed to march into the future. Climate change requirements indicate that prediction times may reach beyond decades, including increased resolution to determine smaller scale events. Given the many experiments needed to develop a successful model (GCM), a more efficient integration scheme seems essential. Our effort at reconstructing the prediction system to optimally use 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 massively parallel processor with unlimited processors, the computing cycle would include all the calculations that would not need repetition by their dependence on previous calculations. For conventional marching problems, barring instability, the minimum computing cycle could be as small as one complete time step. It is this computing cycle that we attempt to approach.

We first 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 that would allow a computation to be made in one machine cycle. The formula was represented by a Taylor Series (TS) and developed by repeated differentiation using Mathematica (Wolfram, 1991). A number of experiments were performed with alternate modeling conditions and we compared the solution by the TS method to the leapfrog scheme, requiring both methods to yield results within ten percent of the exact solution. The time step achievable with the TS method was seven to ten times longer than that used for the leapfrog scheme. The experiments were repeated using the model on the sphere, and the results were comparable to those with the Lorenz model. These results were presented in a MS thesis by Bing Zhang (1993).

We next proceeded to the shallow water equations. We represented the equations in spectral form using an expansion in Hough modes, first suggested by Kasahara (1977). Following a recommendation by Daley (1980), we split the spectrum of waves into high and low frequency domains, predicting the low frequencies and balancing the high frequencies. For time prediction we again tested the TS approach. A reference calculation was made using the leapfrog scheme with a time step of three minutes, which was much smaller than any of the linear periods of the model. Integrations for short periods (six days) and for longer times (up to 360 days) were performed. When an additional term in the TS was added, the accuracy improved. Alternately, for a given order of accuracy, an additional term in the expansion allowed for a longer time step. These results were presented by Baer and Zhang (11th AMS/NWP Conf., 19-23 August 1996, Norfolk, VA) and by Baer (5Th Workshop on PDEs on the sphere, 12-14 June, 1996, Breckenridge, CO).

The TS expansion method with higher derivatives becomes cumbersome when applied to GCMs. We thus developed an alternate technique using only the initial values of the model dependent variables and their first order time derivatives for determining the coefficients for the TS; it is a multi-level time integration scheme. We tested this scheme with the Lorenz system. First we integrated the system by using the regular leapfrog scheme with a short time step of 3 minute as good estimator for exact solutions. Since the numerical solutions are periodic, we integrated 150-200 period lengths, calculating the average periods, amplitudes and time means of model output as reference. We ran the Lorenz system with the same initial conditions using our multi-level time integration scheme and the high order leapfrog and forward time integration schemes with longer time steps. We discovered that we were able to gain a threefold advantage in the time step by use of the multi-level time integration scheme.

We then applied the multi-level scheme to the spectral shallow water model using the Hough mode expansion. The multi-level scheme was applied to the Kasahara model and we split the system into slow and fast equations, using balancing to exceed the CFL limit on high frequency motions. In these control experiments the Hough modes are eigenfunctions of the linearized version of the original shallow water equations with no basic flow. But the eigenmodes are strongly dependent on the basic state (Kasahara, 1980). Therefore we linearized the spectral shallow water equations with respect to mean states from reference runs by use of a forward-difference approximation to the linear Jacobian operator and solved the linearized equations to get normal modes. We used these normal modes for expansion to construct a new spectral model. This approach has general applicability independent of spectral or grid representations of the original model. We defined the 500 low-frequency modes of the total 2520 normal modes as slow modes and the remainder as fast modes. For the fast modes, we treated the linear part of the equations analytically to achieve numerical stability (Daley, 1980). For the slow modes, we integrated the equations with both the regular leapfrog scheme and our multi-level time integration scheme. The time step could be expanded to about 40-80 minutes for both time integration schemes, a 10-20 fold increase in the time step. Only a 1-3 gain in computing time was noted with a single CPU computer because of the penalty per time step cycle for the multi-level scheme. However this penalty can be removed using MPP architecture.

Analyzing monthly data archives from four year model runs, including control runs, leap-frog and multi-level time integrations, we noted that the differences in the statistical characteristics such as time means and standard deviations among the control run and the different time integration schemes based on the same initial condition was small for all the initial conditions tested, although the multi-level scheme was better than the leap-frog scheme on the whole. We also calculated the rms difference against a control run for the first 30 days and found the multi-level scheme to be far superior to the leapfrog scheme.

D. Optimum realization statistics

As indicated by our interest in the ensemble nature of the climate problem and that meaningful climate statistics require many realizations, we undertook to examine the possibility that by suitable representation of model output, some reduction in the number of realizations necessary to achieve meaningful climate statistics might be feasible. This was stimulated by the repeated observation that if model variables are expressed spectrally, amplitude variations seem to be more robust than phase and that phase variations for smaller scales tend to be exceptionally large. We set out to check this hypothesis from archived model simulations represented in spectral space and we chose the expansion in solid harmonics since often these are the actual functions used in the numerical integration. The presumption behind this endeavor is that if amplitude does not vary substantially amongst the realizations, then if amplitude is an adequate measure of climate, many fewer realizations might be needed. Clearly this reduction in computer time would be welcome in resolving the climate prediction problem. Note the relationship of this endeavor to our study on concurrent climate simulations.

From a many year integration archive of a two level baroclinic model, we selected 80 realizations of the mean and shear stream field as our ensemble data set. Each spatial field of the ensemble was converted to spectral form and stored as amplitude and phase. The amplitudes were averaged over the ensemble and a standard deviation field was constructed. The ratio of the standard deviation of each spectral coefficient amplitude to its mean value was recorded. The spatial patterns of the same realizations were then averaged and a standard deviation pattern was created. Both the mean spatial pattern and its standard deviation field were spectrally decomposed and the ratios of the amplitudes of the standard deviations to the means were calculated. The results of the experiment highlighted the fact that the ratios developed from the amplitudes of the spatial fields were substantially larger than the ratios determined from the averaged amplitudes. This was true for each of the climate averaging periods we considered. Since averaging the spatial fields incorporates changes in phase as well as amplitude, the implication of the results corroborates our hypothesis insofar as many ensemble calculations are needed primarily to overcome variability in phase predictability. If amplitude patterns are sufficient to determine climate statistics, only very few realizations may suffice to yield meaningful results.

We confirmed that these results did not depend significantly on model truncation, repeating the analysis with archives from the same model running at truncations of T31, T42 and T63. However it was still necessary to establish if our findings would be corroborated with more climatically realistic models. For this purpose, we had available 9 realizations of 45-year integrations (as well as 12 realizations of 11 years) of the NMC forecast model. We processed this data similarly to the way we analyzed the archived model data described above, concentrating on the surface temperature and the 200 and 500 hPa geopotential heights. Our conclusions on climate variability in amplitude and phase were confirmed from the analysis of output from this more realistic model. Moreover the large variability in phase was also confirmed from independent analyses of the spectral phase data.

E. Parameterization studies

As an adjunct to our efforts to improve models from a representational and computational viewpoint, we have also studied a number of issues relating to forcing in the atmosphere which may assist us in parameterizing those processes which cannot be developed by a model in complete detail. Since the tropics are a primary source for such forcing, we have focused most attention on them, including the EL NINO phenomenon.

1) On The Longitudinal Placement Of El Nino-Related Pacific Streamfunction Anticyclones In Summer Months;

Of the upper-tropospheric flow patterns associated with El Nino, the anticyclone pair straddling the equator in the central Pacific is perhaps the most prominent. The question of why the anticyclones occur is not generally debated, since Gill's (1980) simple linear model produces similar anticyclones in response to an idealized heat source centered on the equator. Debate has instead focused on the longitudinal placement of the anticyclones, since the Gill model produces anticyclones well to the west of their observed position. Several authors have addressed the longitudinal placement question for the wintertime (DJF) El Nino anticyclones (e.g., Hendon 1986, Sardeshmukh and Hoskins 1985). These authors generally regard the Gill model as an oversimplification, pointing in particular to the importance of neglected nonlinear terms. However, they still retain the basic precept, referred to here as the Gill hypothesis, that the anticyclones represent a local response to local heating centered on the equator.

In this study, we test the Gill hypothesis for the El Nino- related anticyclones found in summer months. First, we first produce composite anticyclones for the summer months by regressing 200mb streamfunction against a tropical Pacific OLR index. We then we use a steady linear diagnostic model to simulate the anticyclones given the corresponding OLR-covariant forcing terms, primarily the residually diagnosed heating field. The model is linearized about a zonal-mean climatological basic state. For these months, the linear model produces a reasonable simulation of the anticyclones.

The two summer months in which the anticyclones are most prominent are May and August. In August, when the anticyclones are centered well to the west of the dateline, the Gill hypothesis is essentially correct: the longitudinal placement of the anticyclones is well simulated when the model is forced by local, equatorially centered heating anomalies. However, we find that El Nino-related cooling anomalies, generally not discussed in the wintertime studies, are just as important as El Nino- related heating in determining the central longitude of the anticyclones.

In May, when the anticyclones are centered to the east of the dateline, the Gill hypothesis is found to be incorrect: the anticyclones are forced primarily from the northern tropics and subtropics. This remote forcing consists of anomalous cooling over the western tropical Pacific and Southeast Asia, and anomalous heating over the subtropical Atlantic. Our study thus shows that the El Nino-related anticyclones are not necessarily a response to local, equatorially centered heating anomalies, even when heating anomalies of both signs are considered. Results of this research were presented at the Eighth Symposium on Global Change Studies, and at the 1997 Joint Assemblies of IAMAS and IAPSO.

2) Effect Of Mountain Ranges On The Midlatitude Atmospheric Response To El Nino Events;

To gain better insight into how parameterization might be effectively used in Global Climate prediction and how efficiencies in computation in this arena might be applied, we have considered the barotropic modeling of the interaction of tropical-heating induced by stationary waves with mid-latitude orography. Tropical heating associated with El Nino events can excite large amplitude stationary waves that extend well into the extratropics. However, these directly forced stationary waves do not explain the upper level streamfunction anomalies that occur during El Nino winters. To generate the observed anomalies, the directly forced patterns must undergo secondary interactions with other components of the climate system. We have thus investigated the modification of the extra-tropical response to tropical heating by a secondary interaction with mid-latitude orography. Using a steady barotropic anomaly model, we found that this interaction, occurring primarily in the Himalayan-Tibetan region, generates circulation anomalies which resemble the observed circulation anomalies, including a four-celled pattern over the Pacific/North American section with height anomalies in excess of 40 geopotential meters. The associated zonal wind anomalies reach 6m/sec in the central Pacific, where they act to extend the jet southeastward, as is typical in El Nino winters. Results of this research were published in Nature (see DeWeaver and Nigam, 1995).

As a follow-up to this study (see Nigam and DeWeaver, 1997) we tested the sensitivity of the above orographic interaction to a variety of factors. The principal finding of this study is the orographic interaction is sensitive to the specification of the extratropical convergence in the model. This convergence is required to offset the tropical divergence so that the net global mean divergence anomaly is zero. The sensitivity is partly a consequence of the interaction between the eddy and zonal-mean components of the flow anomaly simulated by the model.

3) Dynamics Of Zonal-Mean Flow Assimilation;

Further insights on potential parameterization were gained from a study of the causes and dynamical implications of differences between NASA/GEOS assimilated and ECMWF analyzed 200mb divergent circulations during recent El Nino/La Nina winters. The Data Assimilation Office at the Goddard Laboratory for Atmospheres has recently produced an atmospheric data set for the years 1985 to 1993 using a fixed assimilation system known as the Goddard Earth Observing System Data Assimilation System (GEOS-DAS). The data set is produced using a novel method, the Incremental Analysis Update (IAU) procedure, in which observed data are fed gradually into a model integration as external forcing functions. We diagnosed the seasonally averaged 200mb circulations for recent El Nino (1987/88) and La Nina (1988/89) winters (DJF) using both GEOS-DAS and ECMWF data to determine whether there are significant differences in the dynamics of the zonal-mean circulation revealed by the two data sets, and whether these differences are related to the IAU method. We found that the IAU method is not adequate to assimilate the Hadley circulation. This result is demonstrated using an idealized model of a zonally symmetric assimilation in log-pressure coordinates. The finding is borne out by a comparison of GEOS-DAS assimilation, analysis, and first-guess fields, in addition to the comparison with the ECMWF wintertime Hadley cell. An alternative assimilation method is proposed for the zonally symmetric circulation, in which thermal and mechanical forcing functions are constructed from the difference between first guess and analysis estimates of potential vorticity and secondary circulation. Results of this research were published in J. Atmos. Sci. (see Deceiver and Enigma, 1997).

F. The impact of subgrid scale motions and their parameterization in atmospheric models

NWP and climate models require subgrid scale parameterization for numerical closure. If the effects of such closure are clearly understood, both computational benefits and improved forecasts could ensue. To investigate parameterization of subgrid scale momentum transport, we attempted several parameterization schemes for the spectral barotropic vorticity equation (BVE). We used versions that were unforced, forced by topography, and forced by topography and negative dissipation in the synoptic scales (simulating forcing by baroclinic eddies). First, reference integrations were performed at T63 truncation. Then, integrations were carried out from the same initial state at lower truncations, T42 and T31. Finally, integrations were performed at T42 and T31 with parameterized spectral coefficients in the ranges $42 \leq n \leq 63$ and $31 \leq n \leq 63$. The ability of the lower order systems with and without parameterization to mimic the behavior of the full T63 system was compared using a KE error ratio for each total wavenumber n. Parameterization generally consisted of regressing either the small scale coefficients or their tendencies against the larger-scale flow components. In one scheme, the exact coefficients of the high-order integration were used (the "omniscient scheme"). In all cases, eighth order dissipation was applied to the smallest predicted scales.

Two results stand out significantly: first, if the models with parameterization were run at the reduced cutoff scale but without the parameterization, the results were comparable to those with parameterization. This was the case even with the "omniscient" scheme. Second, if the reference model was run with the initial data set to zero in the small scales which represent the subgrid domain of a reduced resolution model, the results of the integration were very similar to the reference model results which included nonzero data, 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. Results of this research were presented at the American Meteorological Society's Tenth Conference on Numerical Weather Prediction.

III. References

Baer, F., 1970: Dependence of the highly truncated spectral vorticity equation on initial conditions. *J. Atmos. Sci.*, **27**, 987-999.

Bretherton, F.P., 1982: Ocean Climate Modelling. *Progress in Oceanography*, **11**, 93-129.

CHAMMP, Program Plan, 1990: Building an advanced climate model. Climate Modeling Program, DOE, AER, Washington, DC, 70 pp.

Daley, R., 1980: The development of efficient time integration schemes using model normal modes. *Mon. Wea. Rev.*, **108**, 100-110.

DeWeaver, E., and S. Nigam, 1995: Influence of mountain ranges on the mid-latitude atmospheric response to El Nino events. *Nature*, **378**, 706-708.

DeWeaver, E., and S. Nigam, 1997: Dynamics of zonal-mean flow assimilation and implications for winter circulation anomalies. J. ATMOS. SCI., **54**, 1758-1775.

Gill, A. E., 1980: Some simple solutons for heat induced tropical circulations. *QJRMS*, **106**, 447-462.

Haidvogel, D. et al., 1997: Global modeling of the ocean and atmosphere using the spectral element method. to appear, *Atmosphere-Ocean*.

Held, I., and M. Suarez, 1994: A Benchmark calculation for the dry dynamical cores of atmospheric general circulation models. *Bull. Amer. Met. Soc.*, 1825-1830.

Hendon, H. H., 1986: The time-mean flow and variability in a nonlinear model of the atmosphere with tropical diabatic forcing. *J. Atmos. Sci.*, **43**, 72-88

Iskandarani, M., et al., 1995: A staggered spectral finite element model with application to the oceanic shallow water equations. *Int. J. Numer. Methods Fluids*, **20**, 393-424.

Kasahara, A., 1977: Numerical integration of the global barotropic primitive equations with Hough harmonic expansion. *J. Atmos. Sci.*, **34**, 687-701.

Kasahara, A., 1980: Effects of zonal flows on the free oscillations of a barotropic atmosphere. *J. Atmos. Sci.*, **37**, 917-929.

Lorenz, E. N., 1960: Maximum simplification of the dynamic equations. *Tellus*, **12**, 243-254.

Nigam, S., and E. DeWeaver, 1998: Influence of orography on the extratropical response to El NINO events. *J. Clim.*, **11**, 716-733.

Saravanan, R., 1993: Equatorial superrotation and maintainance of the general circulation in two level models. *J. Atmos. Sci.*, **50**, 1211-1227.

Sardeshmukh, P. D., and B. J. Hoskins, 1985: Vorticity balances in the tropics during the 1982-1983 El Nino-Southern Oscillation event. *QJRMS*, **111**, 261-278.

Taylor, M., J. Tribbia and M. Iskandarani, 1997: The spectral element method for the shallow water equations on the sphere. *J. Comput. Phys.*, **130**, 92-108.

Wolfram, S., 1991: Mathematica. Addison-Wesley Press, New York, ISBN 0-201-51507-5, 961 pp.

Williamson, D., et al., 1992: A standard test set for numerical approximations to the shallow water equations in spherical geometry. *J. Comput. Phys.*, **102**, 211-224.

IV. Publications

Baer, F., and E. DeWeaver, 1994: The impact of subgrid scale motions and their parameterization in atmospheric models. PROCEEDINGS OF THE TENTH CONFERENCE ON NWP, 17-22 July 1994, Portland, OR, Boston, MA, p. 389-391.

Baer, F., and Wm. Campbell, 1994: Experiments In Optimum Three-Dimensional Model Truncation. PROCEEDINGS OF THE TENTH CONFERENCE ON NWP, 17-22 July 1994, Portland, OR, Boston, MA, p. 41-43.

Baer, F., 1996: Experiments in optimum three-dimensional truncation. MODERN DYNAMICAL METEOROLOGY, Proceedings from a Symposium in honour of Professor Aksel Wiin-Nielsen, Copenhagen, Denmark, 1995, Ed. by Peter D. Ditlevsen, pp 9-14.

Baer, F., Banglin Zhang and Bing Zhang, 1998: Optimizing computations in weather and climate predictions models. METEOROL. ATMOS. PHYS., **67**, 153-168.

DeWeaver, E., 1994: On the dynamics of extratropical low-frequency atmospheric variability. MS scholarly paper, Dept. of Meteorology, U. Of Maryland, 25pp + figures.

DeWeaver, E., and S. Nigam, 1995: Influence of mountain ranges on the mid-latitude atmospheric response to El Nino events. NATURE, **378**, 706-708.

DeWeaver, E., and S. Nigam, 1997: Dynamics of zonal-mean flow assimilation and implications for winter circulation anomalies. J. ATMOS. SCI., **54**, 1758-1775.

DeWeaver, E., and S. Nigam, 1999: Do stationary waves drive the zonal-mean jet anomalies of the northern winter? Submitted to JOURNAL OF CLIMATE.

Ehrendorfer, M. and J. Tribbia, 1996: Optimal Prediction of Covariances through Singular Vectors. J. ATMOS. SCI., **54**, 286-313.

Haidvogel, D., E. Curchitser, M. Iskandarani, R. Hughes and M. Taylor, 1997: Global modeling of the ocean and atmosphere using the spectral element method. ATMOSPHERE-OCEAN, **35**, 505-531.

Mizzi, A., J. Tribbia and J. Curry, 1995: Vertical Spectral Representation in Primitive Equation Models of the Atmosphere. MON. WEA. REV., **123**, 2426--2446.

Nigam, S., and E. DeWeaver, 1998: Influence of orography on the extratropical response to El NINO events. J. CLIM., **11**, 716-733.

Spotz, B., M. Taylor, and P. Swarztrauber, 1988: Fast shallow-water equation solvers in latitude-longitude coordinates. J. COMP. PHYS., **145**, 432-444.

Taylor, M., 1995: Cubature for the sphere and the discrete spherical harmonic transform. SIAM J. NUMER. ANAL., **32**, 667-670.

Taylor, M., J. J. Tribbia and M. Iskandarani, 1997: The spectral element method for the shallow water equations on the sphere. J. COMPUT. PHYS., **130**, 92-108.

Taylor, M., R. Loft and J. J. Tribbia, 1998: Performance of a spectral element atmospheric model (SEAM) on the HP Exemplar SPP2000. NCAR/TN-439+EDD, 9pp + figs.

Taylor, M., and B. Wingate,1998: A generalized diagonal mass matrix spectral element method for non-quadrilateral elements. Submitted to APPL. NUM. MATH.

Taylor, M., and B. Wingate, 1998: The Fekete collocation points for triangular spectral elements. Submitted to SIAM J. NUMER. ANAL.

Tribbia and Taylor, 1977: "Localized Mesh refinement in a global spectral element primitive equation model," in preparation.

Zhang, Bing, 1993: Use of Taylor expansion in computation of the simple spectral barotropic vorticity equation. MS scholarly paper, Dept. of Meteorology, U. Of Maryland, 14pp + tables and figures.

V. Research staff

In addition to the PIs, the following individuals worked on the grant:

Research scientists; Mark Taylor, Francois Thibaud, and Banglin Zhang and Aime Fournier.

Students; Eric DeWeaver and Bing Zhang. DeWeaver received MS and PhD degees and Zhang received an MS degree.

VI. Attendance, participation and presentations at meetings and workshops (1994-1997)

Ferdinand Baer

- AMS Annual meeting, Jan. 94, Nashville, TN
- CHAMMP STM, Apr. 25-29, 1994, Albuquerque, NM; Report on CHAMMP project.
- Meteo France, Toulouse, 27-28 June, 1994 and MPI, Hamburg, 6 July 1994; gave lectures in both places.
- 10th AMS/NWP Conf., 18-22 July, 1994, Portland OR; Chaired session; paper presentation, "Experiments in optimal three dimensional model truncation"; poster presentation, " The impact of subgrid scale motions and their parameterization in atmospheric models" (with E. DeWeaver).
- 4Th CHAMMP workshop, PDEs on Sphere, 24-26 Aug., 1994, Chicago, IL
- ARM-CHAMMP Workshop, 12-13 Oct. 1994, Boulder, CO
- Climate diagnostics workshop, 14-18 Nov. 1994, College Park, MD
- Symposium in honour of Professor Aksel Wiin-Nielsen, Copenhagen, Denmark, May 8-12, 1995; presentation entitled, "Experiments in optimum three-dimensional truncation."
- IUGG, Boulder, CO, July, 1995.
- 3Rd Int. Conf. On Modeling of global climate change and variability, 4-8 Sept. 1995, Hamburg, Germany; gave a presentation.
- CHAMMP STM, Rockville, MD, October 2-4, 1995.
- Climate Diagnostics Workshop, 23-27 Oct. 1995, Seattle WA; presented a poster.
- EGS General Assembly, 6-10 May, 1996, The Hague, Netherlands. Gave a presentation with Thibaud.
- 5Th Workshop on PDEs on the sphere, 12-14 June, 1996, Breckenridge, CO; Presentation: "Optimizing time integration schemes".
- 11th AMS/NWP Conf., 19-23 August 1996, Norfolk, VA, "Optimizing time integration schemes for NWP" (with B. Zhang, and presented by him).
- CSM Atmospheric modeling working Group meeting, Jan. 14-15, 1997, Boulder, CO; gave a presentation and visited our CHAMMP group at NCAR.
- AMS annual meeting, 2-7 Feb., 1997, Long Beach, CA; gave a presentation.
- CHAMMP Science Team Meeting, 3-7 March 1997, San Antonio, TX.
- 22nd General Assembly, EGS, 21-25 April 1997, Vienna, Austria; presented a paper.

Joseph J Tribbia

- AMS Annual meeting, Jan. 94, Nashville, TN.
- Courant Institute GFD Seminar-February 1995: Uniformly Valid Global Filtered Models; discuss CHAMMP issues

- Courant Institute Applied Math Seminar -February 1995: On Slow and Inertial manifolds; discuss CHAMMP issues
- NCAR Statistics Project Seminar-February 1995: An Alternate Explanation of Atmospheric Multimodality; discuss CHAMMP issues
- University of Copenhagen Wiin-Nielsen Symposium-April 1995: An Alternate Explanation of Atmospheric Multimodality; discuss CHAMMP issues
- CNR Modena, Italy Seminar-April 1995: An Alternate Explanation of Atmospheric Multimodality; discuss CHAMMP issues
- Departmental Seminar: ISU-April 1996: An Alternate Explanation of Atmospheric Multimodality; discuss CHAMMP issues
- FALL AGU Invited Presentation: San Francisco- December 1996: Regime Transitions: Forecastability and Predictability
- Departmental Seminar: Univ. Wisconsin-February 1997: Forecasting Error Covariances using Ensemble Methods
- SIAM Meeting Mathematical Geosciences: Albuquerque-June 1997: Nonlinear Statistical Problems in Meteorology.

Mark Taylor

- AMS Annual meeting, Jan. 94, Nashville, TN; Presentation: "Investigations of climate predictability".
- Fourth Workshop on Numerical Solutions of Fluid Flow in Spherical Geometry, Chicago IL, August 1994; Presentation:
- "The spectral element method for the shallow water equations on the sphere."
- CHAMMP Science team and model development meeting, Rockville, MD, October 1995; Presentation: "The spectral element method for the shallow water equations on the sphere."
- Physical Oceanography Meeting, Rutgers, NJ, November 1995; Presentation: "Atmospheric modeling with SEOM."
- 102nd Annual Meeting of the AMS, special session on Computational harmonic analysis and approximation theory, Orlando, FL., January 1996; Presentation: "Spherical harmonic spectral methods."
- Applied and Computational Sciences Research Seminar, Colorado School of Mines, April 1996; Presentation: "The spectral element method for atmospheric and oceanographic modeling."
- Fifth Workshop on Numerical Solutions of Fluid Flow in Spherical Geometry, Breckenridge CO June 1996; Presentation: Test case results and localized mesh refinement for the spectral element method on the sphere."
- The BEAVIS Seminar, Dartmouth College, Hanover NH, October 1996; Presentation: "Quadrature and the spectral element method."
- CHAMMP Science team and model development meeting, San Antonio, TX, March 1997; Presentation: "Investigations of climate predictability"

DeWeaver, Eric

- American Meteorological Society's Tenth Conference on Numerical Weather Prediction, Portland, OR, July 17-22, 1994, Presentation: "Impact of subgrid scale motions and their parameterization in atmospheric models," (first author, F. Baer).
- European Geophysical Society, Hamburg, 3-7 April, 1995; Presentation: "Experiments in optimum three-dimensional model truncation", (co-author, F. Baer).
- Tenth Conference on Atmospheric & Oceanic Waves and Stability, Big Sky, Montana, June 5–9, 1995; Presentation: "Barotropic modeling of the interaction of tropically forced rotational flow with orography," (co-author, S. Nigam).
- Twentieth Annual Climate Diagnostic Workshop, Seattle, WA, October 23–27, 1995; Presentation: "Diagnostic modeling of the interaction of tropically generated circulation anomalies with midlatitude mountains and oceans," (co-author, S. Nigam).
- American Meteorological Society's Symposium on Global Ocean-Atmosphere-Land System (GOALS), held in Atlanta, GA, Jan. 28–Feb. 2, 1996; Presentation: "Interaction of tropical heating induced atmospheric flow with midlatitude orography," (co-author, S. Nigam).
- American Geophysical Union, spring meeting, Baltimore, MD, May 20-24, 1996, Presentation: "Diagnostic modeling of the interaction of tropically generated circulation anomalies with midlatitude mountains," (co-author, S. Nigam).
- American Geophysical Union, spring meeting, Baltimore, MD, May 20-24, 1996, Presentation: "Differences between NASA/GEOS assimilated and ECMWF analyzed divergent circulations: causes and dynamical implications for El Nino wintertime anomalies," (co-author, S. Nigam).
- 21st Annual Climate Diagnostics and Prediction Workshop, Huntsville, AL, October 28-November 1, 1996, Presentation: "Differences between NASA/GEOS assimilated and ECMWF analyzed divergent circulations: causes and dynamical implications for El Nino wintertime anomalies," (co-author, S. Nigam).
- American Meteorological Society's Seventh Conference on Climate Variations, Long Beach, CA, Feb. 2-7, 1997, Presentation: "Differences between NASA/GEOS assimilated and ECMWF analyzed divergent circulations: causes and dynamical implications for El Nino wintertime anomalies," (co-author, S. Nigam).
- American Meteorological Society's eighth symposium on global change studies, Long Beach, CA, Feb. 2-7, 1997, Presentation: "On the longitudinal placement of El Nino-related Pacific streamfunction anticyclones in summer months," (co-author, S. Nigam).
- "Dynamics of zonal-mean flow assimilation and implications for wintertime circulation anomalies". Seminar presented to the Data Assimilation Office at NASA/GSFC, May 23, 1997.
- "On the longitudinal placement of El Nino-related Pacific streamfunction anticyclones in summer months," Joint Assemblies of IAMAS and IAPSO, Melbourne, Australia, July 1-9, 1997. (co-author, S. Nigam).