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EXPLOITATION OF PARALLELISM IN CLIMATE MODELS

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Introduction

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 MPP's 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.

This report summarizes the activities of our group during a part of the first year's effort to meet the objectives stated in our proposal. We will comment on the three research foci, time compression studies, subgrid scale model studies, and distributed climate ensemble studies and additional significant technical matters.

Time Compression Studies

The techniques necessary to utilize massively parallel processors for solving the climate prediction problem exploiting *established* numerical processes and state-of-the-art models seem now to be well understood and have been explored to a significant extent. Unfortunately, even if one optimizes current and near future MPPs, the need for adequate computer processing time may not be met. This limitation is based on the fact that currently models are solved as a marching problem in time, and no matter how fast we can compute results in a given time step, we are limited in time by the number of steps needed to march into the future; and climate change requirements indicate that the prediction time must be increased to the order of tens of years. One possible solution to this bottleneck is to reconstruct the forecast system so that many time levels may be computed concurrently, i.e., in a given machine cycle provided sufficient processors are available.

Our purpose is then to use as few time cycles as possible to complete a model integration. How can the time cycles be compressed? Let us define the "computing cycle" to be that time

required to do once all the calculations which must systematically be repeated to complete the entire calculation. 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 as a limit for an integration.

We have approached this problem during the current grant year by considering the barotropic vorticity equation (BVE) in both spectral and interaction coefficient form. This simplification is based on the desire to *uncomplicate* the problem of nonlinearity so that the basic procedure can be identified. The relevant equation which is listed as equation (1) in our proposal is as follows:

$$\frac{d\psi_i}{dt} = \sum_{j,k} \psi_j \psi_k I_{i,j,k}$$

Note that one can differentiate this equation as many times as desired and by iteration can represent the highest derivative by a series of the coefficients (ψ_i). Now consider an expansion of any coefficient by Taylor's series,

$$\psi_i^{(n\Delta t)} = \psi_i(o) + \frac{d\psi_i}{dt}(o)\ n\Delta t + \frac{d^2\psi_i}{dt^2}(o)\frac{(n\Delta t)^2}{2!} + \cdots$$

and take the series for n terms. In terms of initial values, $\psi_i(o)$, a series can be expressed in terms of products and powers of the initial values and the appropriate constants $I_{i,j,k}$. The particular examples we have focussed on is a low-order version of the BVE which has the form,

$$\frac{d\psi_i}{dt} = a_i \psi_j \psi_k \qquad 1 \le i,j,k \le 3.$$

This represents three equations where we permute the indices i, j and k such that j = i + 1, k = j + 1 and i + 3 = i, etc. The prediction system, using the Taylor's expansion can be given as

$$\psi_i^{n\Delta t} = \sum_{l=1}^{n+1} A_l X_l (\Delta t)^{l-1}$$

and the A_ℓ are known constants of n, ℓ. The X_ℓ are calculated from the initial values $\psi_1(o)$, $\psi_2(o)$, $\psi_3(o)$ in the form

$$X_\ell = \sum_{m=o}^{\ell-1} G^\ell[\psi_1(o),\psi_2(o),\psi_3(o)] L_m^{(\ell)} .$$

We have shown that we can perform the entire calculation in only a few machine cycles of a MPP of sufficient capacity by utilizing as many processors as possible, whereas the conventional computational procedure would take a minimum of n cycle on an MPP and many more on a serial machine. We are currently extending this technique to high order systems of the BVE.

Another procedure taken by analogy from the computational treatment of spatial scales, is to expand the time variability of the model dependent variables in some series, either a general polynomial or special functions as for example Fourier series. Substitution of such series into the prediction equations and integration over a specified prediction period would lead to a set of coupled equations for coefficients which could in principle be calculated in one computing cycle, where one computing cycle is the absolute minimum computing time to which any calculation can be reduced. A restructuring of the forecast equations in this format could give us substantial information on how to proceed with the nonlinear computations. We may discover appropriate time scales for each space scale so that variable expansions for the space scales could be used. Additionally, we should discover the relevant time subinterval over which an expansion should be appropriate, and thus apply the procedure repeatedly for a number of sub-periods. We will continue this approach over the coming months.

Subgrid Scale Model Studies

All nonlinear models need some form of closure on space scales to allow a computation to proceed. This is effected by subgrid scale parameterization and is done a variety of ways, principally designed however to avoid computational difficulties. 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.

Regional scales must be studied independently of the global scales. The principal forces which the subscale domain imposes on the global model and the time scales over which the subgrid scale can be averaged must be established. Since the subgrid scale domain is locally space dependent, domains which are sufficiently homogeneous to be included in any one model must be identified and a set of such regionally dependent models developed. Due to high frequency properties of these models non hydrostatic effects should be included.

We have begun to conceptualize a global climate model of the atmosphere with its associated interactive models and truncated at a reasonable scale to include meaningful regional climate areas. A set of regional models is concurrently under development to encompass spatial scales not included in the global model. These models are to include the uniqueness and homogeneity of the local region they represent, and their number in sum spans the entire space of the domain of the global model. This research is just beginning and will be accelerated in the near future. We hope to get substantial assistance from the appointment of a postdoctoral fellow.

Distributed Climate Ensemble Studies

The inherent ensemble nature of the climate problem suggests the use of machines with massively parallel architecture. The traditional manner in which the climate ensemble is generated in general circulation models mimics 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 man 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.

We have just begun to develop low-resolution/simple models for integration 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. We have also begun to address the "judicious choice" of initial states. We are constructing initial states using the most important modes of climate variability. By constructing initial states in this fashion we will guarantee the independence of the ensemble elements as they evolve in time and thus sample different portions of the climate probability distribution.

Science Team Activities

The science team members on this project have met on several occasions at NCAR (October, November 1991; January, February 1992) thanks to other activities which brought Professor Baer to Colorado. In addition to outlining and planning our scientific effort at these meetings, we have selected and offered a postdoctoral appointment to Mark Taylor from the

Courant Institute and he will join the project. Unfortunately, he will be somewhat delayed awaiting completion of his dissertation, but we are confident that his ultimate contribution will be worthwhile. We have also completed our search for a programmer and an offer is imminent. Finally, one graduate student from UMCP, Department of Meteorology has been assigned to the project; his name is Bing Zhang.

Two members of the team, Baer and Tribbia will attend the CHAMMP science team meeting in Las Vegas, 16-18 March 1992 and will report on the program to date.

Summary

The project is proceeding as anticipated in the original proposal and gradually picking up speed. Although our accomplishments to date are limited, we have begun to study the details of the time compression problem, have given thought to the nature of subgrid scale models needed for parameterization, and are beginning to develop the distributed climate ensemble strategy. We expect the project to continue as planned during the upcoming year and look for significant results to ensue.

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