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Enhancements to Modeling Regional Climate Response and Global Variability

Principal Investigators DOE Patent Clearance Granted

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The rationale, background and accomplishments which lead to the research reported herein has been clearly stated in both the proposal and the final report to our previous grant; information on that grant can be found under ID ER62022 1004727-0000329. The results discussed below are a continuation of efforts on that grant with a modified emphasis.

I. Introduction

Our efforts during this grant period have focused on three main considerations:

- Developing and testing various climate scenarios with SEAM, our newly created model;
- Model reconstruction efforts to speed up computations;
- Optimum realization statistics.

II. Accomplishments

A. Developing and testing various climate scenarios with SEAM, our newly created model

Our previous CHAMMP grant resulted in the development of SEAM, a spectral element atmospheric GCM dynamical core. We have thoroughly tested SEAM with the shallow water equations and the 3D primitive equations. SEAM makes use of fully unstructured grids, allowing a single low resolution grid to contain areas of higher horizontal resolution. We have demonstrated the effectiveness of this type of localized mesh refinement in the shallow water equations and with the 3D dynamical core for several mountain regions (the Andes and the Himalayas). This gridding capability makes SEAM an ideal tool for studying regional climate. The spectral element method provides a natural way to incorporate local mesh refinement within a global model. Thus regional and higher

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resolution can be achieved (over a limited region) within a global model in a truly interactive fashion and without resorting to any kind of a posteriori nesting or interpolation between different models. This work will thus lead to improved climate simulations by allowing increased resolution in a few dynamically significant regions. Similarly, regional climate simulations will be improved by allowing regional resolution to be incorporated within a global model in a two-way interactive fashion.

The project has proceeded in the following well defined steps:

1. Local mesh refinement for the primitive equations;

We are tested the effectiveness of local mesh refinement using the full 3D primitive equations. We used the Held-Suarez test case forcing together with realistic topography. As expected, the vertical velocity showed unrealistically large Gibbs-like oscillations upstream of steep topography. We completed a suite of long integrations at various uniform global resolutions. These runs were followed by others with very high resolution only near the Andes and the Himalayas, and uniform, lower resolution over the rest of the sphere. The results were similar to those obtained with the shallow water equations but require further testing, which we are now undertaking with a new grant from CCPP.

2. Full fledged climate model;

We were in the midst of replacing the dynamical core of the NCAR CCM3 with SEAM at the termination of the grant and we continue this effort with the new grant referred to above as the first order of business. Once this model is validated, we will have a full featured climate model with complete unstructured grid capability. With this CCM3/SEAM model, we will begin to address the sub-grid scale resolution and parameterization questions mentioned above. The effects of two-way interactions can then be studied by comparing simulations of a one-way nested version of the NCAR CCM to the spectral element version with local enhanced resolution.

3. Completed experiments with SEAM;

3.1 THE SHALLOW WATER MODEL

In addition to the various experiments run with this version of SEAM and which have already been reported previously, a number of tests have been successfully undertaken with semi-implicit integration as contrasted to our previous studies that have used explicit integration. These tests have been performed with assistance from a small group in the Scientific Computing Division at NCAR, and show that substantial speedup can be achieved through this procedure (a factor of three) with no loss of skill. These results may be found in Thomas et al. (2000).

3.2. THE THREE-DIMENSIONAL MODEL

To test the three-dimensional dynamical core of SEAM with simple Zonal forcing as suggested by Held and Suarez (HS, 1994), we used 384 elements distributed uniformly over the globe and with an 8x8 grid in each. This is roughly comparable to a T85 truncation in a spectral model. As with HS, we used 20 equally spaced σ -levels. Comparison of our model output (SEAM) with that given

by HS for both a spectral model (T63) and a finite-difference grid point model (144 points on a latitude circle) show that all three models produce essentially the same results. It was not possible to make a direct comparison of the models' computational efficiency because no such data was available from HS. However, we were able to demonstrate from this experiment that SEAM (in three dimensions) runs very efficiently on a MPP and generates the same number of MFLOPS per processor independently of the number of processors used. Significantly, SEAM computes the HS test case with robust parallel scaling on several parallel machines, out to 24 GFLOPS on 256 processors (Taylor et al. 1998; Fournier et al. 2000a). The average MFLOPS per processor was 130, or 16% of peak, or about 60% above "rule-of-thumb" for RISC processors.

3.3. A POLAR VORTEX

To assess the impact of model forcing greater than simple Newtonian physics used in HS, we ran a primitive equation version of SEAM to determine the structure of Rossby wave breaking in the polar wintertime stratosphere (see Polvani and Saravanan, 2000). The model was dry, forced at the lower boundary to simulate an upward propagating Rossby wave and with various resolutions, ranging from 50-200 vertical levels and horizontal scales of T85 and T181, the latter representing a grid length of about 70 km. The highest-resolution computation used around 2×10^7 mesh points and took 2.5 days on 64 SPP2000 processors, proceeding 6.4 times faster than model-time passage. After 25 days of integration, the model was able to depict in great detail the polar vortices that developed. As the resolution was increased the sharpening of the vortices became more evident. The high resolution encountered by this experiment and its successful prediction demonstrates the robustness of the method. This work has been prepared for publication by Fournier, a member of our research team, and will be submitted soon.

3.4. A BLOCKING EXPERIMENT

Using the three-dimensional dynamical core version of the SEAM with HS conditions at T85 resolution with uniformly distributed elements each having an 8×8 grid, and 10 sigma levels, we carried out ten year integrations with and without a surface topography field of T42 resolution to search for persistent ridges. The ridges found showed a frequency distribution in time similar to those produced by more realistic models (those with more complex physics), although SEAM produced fewer events. Given the model's simplicity, this result was very encouraging. This work is also almost prepared for publication by Fournier and will be submitted soon.

3.5. JETS ON JUPITER

To test the utility of SEAM in successfully calculating the high resolutions required for turbulence studies, we used the SWE version to carry out integrations of decaying turbulence on planet Jupiter with very high resolution. Classical Jupiter dimensions were used ($g = 23 \text{ ms}^{-2}$, radius = $7 \times 10^4 \text{ km}$, Jupiter day = 9 Earth hours) and an equivalent depth of 20,000m was selected, with very weak dissipation. Four different truncations were applied ranging from T170 to T1033. This latter truncation represents 60,000 8×8 elements or roughly 3000 equatorial latitude-circle points. The model ran very efficiently on a Cray T3E with 128

processors, and at that resolution produced multiple jets from pole to pole as anticipated by Rhines (1975,1979).

These experiments indicate that SEAM has the potential to be exceptionally useful for fast high-resolution climate studies, and in particular for embedded regional calculations for both weather prediction and climate study. The SWE tests highlight the efficiency of LMR, the potential accuracy of the method and its ability to take advantage of SMP cluster technology to speed up calculations. The Jupiter study highlights the model's ability to accommodate exceptionally small-scale events over the entire scale range. The studies using the three-dimensional dynamical core indicate that there is no difficulty in extending the method to higher dimensionality, even at very high resolution and with very complex multi-scale dynamics. These results have been published by Baer, Tribbia and Taylor (2001).

B. Model reconstruction efforts to speed up computations

Developing climate prediction model integration schemes that can provide realistic scenarios on long time scales with limited computing resources is a challenge we undertook with this research. We studied a number of methods, reported on earlier, and determined that one of the more promising methods for success in this task is to increase the integration timestep. We tested several techniques that could prove useful. The most successful was applied to the shallow water equations over a spherical surface in which the prediction model was represented in its normal modes. The high frequency modes were balanced while the low frequency modes were predicted. With the success using the shallow water system, we extended this procedure to a state-of-the-art model (the NCAR/CCM3). We took the predicted data from each timestep of the model integration, in this case the CCM3, and projected it onto Hough modes. We then separated the modes into fast and slow components, choosing the cutoff between them based on the timestep desired, and integrated the slow components with a timestep three times longer than that used in the standard CCM3 model run, and balanced the fast modes. This new modal data was then reconverted to model format and returned for the next iteration. Note that it is not necessary to change the model in any way using this procedure. We compared seasonal model integration output using this procedure to the standard model run output and the results from ten realizations showed that both calculations gave identical results within model variability. With additional refinements, integration speedups in excess of the factor of three described here are certainly possible. Detailed results of this study were published by Baer and Zhang (1999).

C. 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.

We were able to document from predictions of atmospheric flow on various time scales, as well as from observations that phase variations are indeed considerably larger than corresponding amplitude variations. With reference to predictions from two separate models, one quite simple and the other a current state-of-the-art model (CCM3), the presumption of larger phase variability was validated. Additionally, a comparable result was established from the assessment of a large data subset of the NCEP reanalysis archives. Based on these evaluations, the result appears to be reasonably robust. Moreover it is mostly insensitive to scale insofar as model truncation is not a significant factor. A number of truncations were tested yielding similar results; adding smaller scales to the predictions proved to be negligible since they contain very little energy. Furthermore, the relative variability of phase when compared to amplitude proved to be comparable for the models tested, with similar values found for the observational (NCEP) data. It should be noted that the test for variability was made indirectly. Amplitude variability was established with and without the inclusion of phase. Since the fluctuations including phase were substantially larger, those fluctuations must be attributable to the variability of phase.

The significance of these results is of some consequence to the prediction of atmospheric events, in particular on the long (climate) scales. With reference to climate prediction, the large variability of phase indicates that a sizeable number of realizations must be made with any climate model to provide a realistic ensemble of predictions from which a meaningful prediction might be extracted. This raises the uncomfortable issue of available computer resources, since many integrations of the same climate scenario must be performed to establish a useful result, and such resources are in short supply and cannot hope to meet the needs of the large climate modeling community. However if the prediction of amplitude alone could prove useful to climate modelers for certain features of climate or for improving climate models, then such calculations can be carried out successfully with far fewer realizations. This would allow modelers to generate more useful model statistics with substantially fewer computing resources. Using such statistics to develop better models may ultimately lead to models which themselves could provide useful climate results with fewer realizations; i.e., the influence of phase on the predictions might be reduced.

With reference to forecasting, since our results indicate that phase is more variable than amplitude, careful attention to the accuracy of phase prediction is essential in assessing the quality of a forecast model. Despite the relative ease of presenting forecast results compactly with amplitude parameters, conclusions drawn from only such statistics could be misleading. The quality of phase prediction needs more emphasis and perhaps given primary consideration if the correct assessment of a forecast model is desired. The result of such an effort may

ultimately require the development of new forecast skills that focus on improving phase prediction, especially if current levels of phase prediction are found to be wanting. In lieu of this development, recent experiments with ensemble forecasting have shown significant success and may be a step in the direction suggested. Indeed the results of our investigation noting the large variability in phase may explain in large part the success of the ensemble method. Since no one forecast can describe the phase prediction accurately, the statistics of the ensemble will pinpoint the predicted phase more accurately. This is consistent with our statement that many realizations are required to achieve a meaningful climate prediction. This research has been submitted for publication by Baer and Tribbia (2002).

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V. Research staff

In addition to the PIs, the following individuals worked on the grant:
Research scientists; Banglin Zhang and Aime Fournier
Student; Eric DeWeaver