

## **Final Report**

### **Closeout of the Award NO. DE-FG02-98ER62618 (M.S. Fox-Rabinovitz, P.I.)**

The following developments have been started and completed since the beginning of the research effort aimed at exploring the variable-resolution stretched-grid (SG) approach to decadal regional and global climate modeling using advanced numerical techniques.

The studies have shown that variable-resolution SG-GCMs using stretched grids with fine resolution over the area(s) of interest, is a viable established approach to regional climate modeling. The developed SG-GCMs have been extensively used for regional climate experimentation. During the proposal period, the joint effort of the U.S. and Canadian collaborators included a productive exchange of the advanced numerical techniques including SG filtering procedures, upper level diffusion formulations, SG-strategies, efficient parallel computing approaches as well as methodologies for the SG-GCM experiments and applications to atmospheric chemistry transport experiments. Joint participation of the U.S. and Canadian proposers in CHAMMP Workshops, CCPP and SciDAC P.I. Meetings, and other events co-organized by DOE as well as the associated productive discussions with another CCPP group led by F. Baer and J. Tribbia, was helpful for structuring the research effort and its coordinated planning.

The dynamical core with realistic orography has been developed and investigated in long-term integrations (Fox-Rabinovitz et al. 2000). Under a companion study, the design of the SG-version (called local mesh refinement/LMR) of the spectral-element (SE) dynamics (Baer et al. 2000, Taylor et al. 1997) was developed by F. Baer, J. Tribbia and Taylor their associates under a separate CCPP effort. The model use the NCAR CAM physics. Using these advanced numerical techniques provides increased computational efficiency for the new SG-GCMs and allows us to employ more flexible stretching strategies beneficial for efficient regional downscaling.

The climate studies based on extensive experimentation with SG-GCMs included: (a) the anomalous regional climate studies of the U.S. Midwest summer drought of 1988 and flood of 1993; (b) the multi-scale analysis of the North American Monsoon System (NAMS); (c) the multiyear ensemble simulation of the U.S. climate; (d) the study of anomalous regional climate events occurred in 1998 for all global quadrants using the new stretched grid design with multiple areas of interest; (e) participation in the PIRCS (Project to Intercompare Regional Climate Simulation) experiment, (f) atmospheric chemistry experiments using SG-products; (g) the study of the U.S. climate using the ensemble simulations, (h) application of the stretched grid approach to the NCAR RegGCM; and (i) participation in PIRCS (Project to Intercompare Regional Climate Simulations).

The above developments and studies as well as other major center/group studies exploring and establishing the stretched grid approach have shown its maturity that allowed the P.I. to initiate and lead since 2001 the international SGMIP-1 (Stretched-Grid Model Intercomparison Project, phase-1) dedicated to studying the U.S. climate.

The following is a more detailed description of the obtained results.

1. Development of the stretched-grid dynamical core with realistic orography (Fox-Rabinovitz et al. 2000)

The impact of introducing a realistic orographic forcing into a uniform- and stretched-grid GCM dynamical core has been investigated by performing long-term and medium-range integrations. Comparisons have been made between various SG-simulations and a control simulation with a uniform grid produced with at high resolution. Results from the region of interest with enhanced resolution show that: the SG-dycore provides an efficient downscaling over the region of interest, that is, it properly represents on only large and medium scales but also the mesoscale features. The introduction of orography has a significant impact and orographic forcing should be considered an integral part of model dynamics.

2. Development of the efficient parallel code for SG-GCM

The parallel code for the SG-GCM is based on that of the basic uniform grid GCM. The modifications related to variable resolution are implemented with no significant impact on model code performance. The access to the ORNL supercomputers has been provided through the SciDAC program. The possibility to run the efficient parallel codes on the ORNL supercomputers is essential for the success of the study.

3. Development of and experimentation with the SG-GCM with multiple areas of interest (Fox-Rabinovitz et al. 2002)

The original SG-design with only one area of interest has been generalized to include multiple areas of interest. The new stretched grid contains four large areas of interest, one within each global quadrant, that ensures a more homogeneous global grid-point distribution. The areas of interest and their vicinities include: the U.S./Southern Canada/Northern Mexico and the surrounding Pacific and Atlantic Ocean areas; Brazil/Northern Argentina/Peru and the surrounding Pacific and Atlantic Ocean areas; India/China/China Sea; Australia/Eastern Indian Ocean. The regions with enhanced resolution include the major monsoonal circulations: the North and South American Monsoon Systems (NAMS and SAMS) as well as the El Nino/La Nino areas, the Indian/Asian, and the Australian monsoon areas.

The SG-generators providing the multiple areas of interest have been implemented into the GEOS SG-GCM and SG-fvGCM. The annual GEOS SG-GCM integration with 50 km regional resolution has been performed for studying the anomalous regional climate events of 1998: the spring drought in the southeastern U.S. and the flood in Midwest and northeastern U.S.; the severe Mexican drought; the severe summer flood over China; the anomalous precipitation events over South America, India, Australia, and African Sahel. The efficient down-scaling to realistic mesoscales is obtained over all four areas of interest while consistent interactions between regional and global scales and the high quality of global circulation, are preserved. The obtained successful simulation results

justify using the stretched grid with multiple areas of interest for future climate studies within this research effort.

The obtained results were presented at: the 82nd AMS Annual Meeting, the 13th Orlando, FL; and at the 4th International Workshop on Next Generation Climate Models for Advanced High Performance Computing Facilities, March 12-14, 2002, Boulder, CO.

4. Regional climate simulations of anomalous events, the 1988 drought and 1993 flood, (Fox-Rabinovitz 2000, Fox-Rabinovitz et al. 2001)

The GEOS SG-GCM experiments have been run with 60 km and 40 km regional resolution over the U.S. and Mexico for the anomalous summer of 1993. Producing mesoscale circulations related to NAMS and their impact on Arizona monsoon as well as the link to Midwest precipitation, were the major goals of the experiments. Using finer, 40 km, resolution was definitely beneficial for producing realistic mesoscale circulations. The low-level-jet over the Gulf of California including its northern part that affects the surges to Arizona, was successfully simulated. The onset and evolution of monsoon precipitation and its negative correlation with precipitation over the Mississippi River basin, were well reproduced.

#### 6. Ensemble SG-GCM integrations

We have started running limited ensemble integrations with a relatively coarse, 60 to 100 km, regional resolution over the U.S. The experiments are run for the 12-year period, 1987-1998, that includes the most recent ENSO cycles. The GEOS SG-GCM surface boundary forcing is obtained from NCEP weekly analyses of SST, snow, and sea-ice, and monthly analyses of soil moisture. The goal of the experiments is analyzing the SG-GCM ensemble integrations in terms of their potential in reducing the uncertainties of regional climate simulation while producing realistic mesoscales. The preliminary results analyzed so far have shown that ensemble means are closer to the verifying analyses and contain realistic mesoscale patterns. However, the optimal size of the ensembles depending on fine regional resolution used, is still to be determined.

7. Atmospheric chemistry transport experiments (K. Pickering, D. Allen, M. Fox-Rabinovitz)

Meteorological fields from the GEOS SG-GCM and SG-DAS are used to drive an off-line Stretched-grid Chemical Transport Model (SG-CTM) that has been developed at the University of Maryland. The SG-approach developed for the GEOS SG-GCM and SG-fvGCM has been successfully implemented for development of the SG-CTM. Using fine-grid resolution over an area of interest is aimed at obtaining a regional downscaling for transport and chemistry.

We have performed simulations with the fine-grid region placed over the central United States to examine transport and tropospheric ozone chemistry associated with the deep convective regime in this region during the summertime. Convective plumes enhanced with pollutants from the boundary layer and ozone photo-chemically-produced in the upper troposphere following deep convection have been traced downstream. These

plumes exit the east coast of the U.S. and are exported to the global troposphere. We have also performed simulations with the SG-CTM with the fine-grid region placed over East Asia and the Western Pacific to examine export of pollutants from the Asian continent to the Pacific and beyond.

#### 8. Application of a stretched grid to the regional NCAR RegGCM (Qian et al. 1999)

A regional stretched grid system has been developed and applied to NCAR RegGCM. The SG-version of the model produced results comparable to a control run with uniform enhanced regional resolution. The computational cost for the SG-system is about 40% lower than that of the uniform grid system due to using smaller lateral buffer area. The numerical experiments with the NCAR RegGCM illustrated the robustness of the SG-approach.

#### 9. Participation in PIRCS (Project to Intercompare Regional Climate Simulations) (Pan, Z., et al. 2002, Fox-Rabinovitz 2000)

The SG-GCM was used for producing seasonal (summer) simulations for the PIRCS endorsed by WMO/WGNE. It allowed us to compare the SG-GCM simulations with those of the participating computationally efficient nested-grid models. The SG-GCM results demonstrate the advantages of the SG-approach to regional climate modeling.

#### 10. Initiation of the international SGMIP-1

The four major center/group models participating in SGMIP-1 are: the U.S. GEOS, Canadian GEM, Meteo-France ARPEGE, and Australian CSIRO C-CAM. The SGMIP 12-year (1987-1998) simulations of the U.S. climate are to be produced at 0.5 degree regional resolution. The SciDAC ORNL terra-scale supercomputers are needed for producing SGMIP results.

### **Refereed publications**

1. Qian, J.-H., F. Giorgi, and M. S. Fox-Rabinovitz, 1999: Regional Stretched Grid Generation and its Application to the NCAR RegCM", *JGR*, v. 104, NO. D6, 6501-6513.

2. Fox-Rabinovitz, M.S., L.L. Takacs, G.L. Stenchikov, M.J. Suarez, and R.C. Govindaraju, 2000: A Uniform and Variable Resolution GCM Dynamical Core with Realistic Orography. *Mon. Wea. Rev.*, Vol. 128, No. 6, 1883-1898.

3. Fox-Rabinovitz, M.S., 2000: Regional climate simulation of the anomalous U.S. summer events using a variable-resolution stretched-grid GCM. *JGR*, Vol. 105, No. D24, p. 29,635-29,646.

4. Fox-Rabinovitz, M.S., L.L. Takacs, G.L. Stenchikov, M.J. Suarez, and R.C. Govindaraju, 2001: A Variable Resolution Stretched Grid GCM: Regional Climate Simulation. *Mon. Wea. Rev.*, Vol. 129, No. 3, pp. 453-469.

5. Fox-Rabinovitz, M.S., L.L. Takacs, and R.C. Govindaraju, 2002: A Variable Resolution Stretched Grid General Circulation Model and Data Assimilation System with Multiple Areas of Interest: Studying Anomalous Regional Climate Events of 1998, *J. Geophys. Res.*, 107(D24), 4768, doi:10.1029/2002JD002177

6. Pan, Z., ... M. S. Fox-Rabinovitz, and other authors, 2002: On PIRCS Models' Consistency of Dynamics with Precipitation. *Amer. Meteor. Soc.*, 13-17.

### **Recent Reports**

Fox-Rabinovitz, M. S., E. H. Berbery, 2001: Regional climate study of the North American Monsoon System (NAMS) with a variable resolution stretched-grid GCM. . *Research activities in Atmospheric and Oceanic Modelling, WMO/TD*, H. Ritchie, Ed., 1064 (31): 7.11-7.12.

Fox-Rabinovitz, M. S., L. L. Takacs, and R. C. Govindaraju, 2002: A variable-resolution stretched-grid general circulation model and data assimilation system with multiple areas of interest: studying the anomalous regional climate events of 1998. *Research activities in Atmospheric and Oceanic Modelling, WMO/TD*, H. Ritchie, Ed., 1105 (32): 1.22-1.23.

### **Recent Conference Presentations**

Fox-Rabinovitz, M. S., L. L. Takacs, and R. C. Govindaraju, 2002: Regional simulation and data assimilation using a stretched-grid approach and ensemble calculations. 82nd AMS Annual Meeting, Orlando, FL, 13-18 January 2002.

Fox-Rabinovitz, M. S., 2002: Variable-Resolution GCMs. The 4<sup>th</sup> International Workshop on Next Generation Climate Models and Advanced High Performance Computing Facilities, 12-14 March 2002, Boulder, CO.

**Recent CCPP PI Meeting:** presentation by M. Fox-Rabinovitz, P.I

San Diego, CA, October 10-13, 2001