Progress report (May 2005) submitted to RIMS

The project is devoted to decadal climate studies using developed and evolving state-of-the-art GCMs (General Circulation Models) with enhanced variable and uniform resolution with advanced numerical techniques that are run on terra-scale SciDAC supercomputers. The variable-resolution stretched-grid (SG) GCMs produce accurate and cost-efficient regional climate simulations using a global stretched grid with enhanced uniform resolution over the region(s) of interest. They have proven to be an established approach to regional climate modeling providing an efficient regional downscaling to mesoscales. The important advantages of variable-resolution stretched-grid GCMs are that they do not require any lateral boundary conditions/forcing and are free of the associated undesirable computational problems. As a result, they preserve the high quality of both global and regional circulations while providing self-consistent interactions between global and regional scales of motion and their associated phenomena as in uniform grid GCMs. The maturity of the SG-approach to regional climate modeling has been established over the last decade through national and international modeling group efforts. The developed SG-GCMs have been extensively used for regional climate experimentation.

This research is devoted to: (a) conducting decadal climate studies on anomalous climate events, in a context of climate variability and predictability, and (b) developing the stretched-grid (SG) GCMs using advanced numerical techniques and ensemble integrations.

The following major issues are addressed in this study: (a) the impact of enhanced resolution on producing consistent global and regional anomalies at meso- and larger scales and their impact on floods, droughts, and monsoonal circulations, when resolving mesoscales; (b) the possibility of providing efficient downscaling capabilities using the stretched-grid approach with consistent interactions of meso- and larger scales; (c) improved understanding and modeling of the processes that affect climate variability and predictability at broad-range temporal and spatial scales; (d) the possibility of reducing uncertainties of global and regional climate simulations using the single- and multi-model ensembles; (e) atmospheric chemistry impacts at mesoscales.

During the report period, the joint effort of the U.S. and Canadian collaborators included a productive exchange of the advanced numerical techniques including SG-strategies, efficient parallel computing approaches as well as methodologies for the SG-GCM experimentation and validation.

The collaboration with J. Cote of (University of Quebec at Montreal (UQAM) and Meteorological Service of Canada (MSC)/RPN) and his group is a strong integral part of the joint effort as well the collaborations with the groups led by M. Deque (Meteo-France) and J. McGregor (CSIRO, Australia). The companion study with the members of another CCPP group, F. Baer and J. Tribbia, is devoted to developing a stretched-grid GCM using the advanced spectral-element technique with variable resolution, and the NCAR CAM physics.

One of the major accomplishments for the report period is the completion of the international SGMIP-1 (Stretched-Grid Model Intercomparison Project, phase-1) conducted as a part of this research activities. SGMIP-1 has been initiated in 2001-2002 and successfully conducted in 2003-2005. It is aimed at in-depth studying the established SG-approach to regional climate modeling. The SGMIP-1 simulations with the U.S. SG-GCM have been produced using SciDAC ORNL supercomputers.

The variable-resolution SG-GCMs participating in SGMIP-1 are the variable-resolution versions of the basic state-of-the-art GCMs of the following four major meteorological centers/groups: Meteo-France ARPEGE, MSC/RPN GEM, Australian CSIRO C-CAM, and the U.S. GEOS. SGMIP-1 has been focused on addressing the following major scientific and computational issues: stretching strategies; approximations of model dynamics; treatment of model physics; multi-model ensemble calculations; optimal performance on parallel supercomputers; studying multiyear U.S. climate events; efficient downscaling to realistic mesoscales.

Regional climate simulations obtained with the state-of-the-art SG-GCMs have been produced for SGMIP-1 with 0.5 x 0.5 degree regional resolution over the major part of North America including the U.S. The results of the successful 12-year (1987-1998) SGMIP-1 multi-model ensemble simulations of the U.S. climate have been processed and analyzed and are available at the SGMIP web site: (http://essic.umd.edu/~foxrab/sgmip.html).

The multi-model SGMIP-1 ensemble results for the region compare well with observations, in terms of both spatial and temporal climate diagnostics. SGMIP-1 provides multi-model ensemble mean results of higher quality than any individual ensemble members. The SGMIP-1 ensemble mean regional biases are mostly limited to 25% - 50% of typical observational errors, while a high quality of global circulation is preserved. The strong coordinated international SGMIP-1 effort involving the U.S., Canadian, French and Australian collaborators led by M. Fox-Rabinovitz, J. Cote, M. Deque, and J. McGregor, puts us in a favorable position for a comprehensive investigation of the diversified impacts on regional climate simulations due to enhanced regional resolution, including the multi-model ensemble results.

The continuation of SGMIP-1 or SGMIP-2 (phase-2) has already began. It includes simulations for longer, 25-year period (1979 to present), with SG-GCMs as well as with high-resolution GCMs. It will provide unique enhanced variable and uniform resolution multi-model regional and global ensembles beneficial for climate modeling community.

Maintaining the developed and evolving SGMIP web site allows us to: (a) disseminate the SGMIP data/products and analysis results to the climate modeling community; (b) make the SGMIP data/products and analysis results available on demand to national and international programs and groups such as WMO/WCRP/WGNE, CLIVAR, and IPCC.

The international SGMIP effort contributes to a scientifically sound and time-and-cost-efficient approach to regional climate modeling and the variety of applications.

The SGMIP effort reflects a trend in climate modeling and broader communities to move towards more detailed regional climate assessments important for the U.S. public, business and policy decision-makers, and for productive international collaborations on climate-related issues.

The SGMIP activities has been presented by P.I. to and endorsed by WMO/WCRP/WGNE at its Meeting during 11-15 October 2004, Exeter, UK.

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

1. Development and further improvement of dynamical cores with advanced numerical techniques

Two variable-resolution SG dynamical cores are under development, one based on the Lin-Rood finite-volume scheme (being developed by P.I. and D. Chalikov) and another with the spectral-element scheme (being developed under another companion DOE/CCPP study

led by F. Baer and J. Tribbia). During the report period both dynamical cores are being adjusted to NCAR CAM-3, with the possibility of using the model with enhanced variable resolution for regional climate studies.

2. SG-GCM ensemble integrations (Fox-Rabinovitz et al. 2005)

Multiyear (1987-1997) limited ensemble integrations using the U.S. SG-GCM, previously developed and experimented with by the participants, are employed for U. S. regional climate simulations. The ensemble members (six in total) are produced at two different regional resolutions: three members with 60 km and other three members with 100 km regional resolution. The use of these two, finer and coarser regional resolutions ensemble members allows us to examine the impact of resolution on the overall quality of the simulated regional fields. For the multiyear ensemble simulations, an efficient regional downscaling to realistic mesoscales has been obtained. The ensemble means of the mid-troposphere prognostic variables (height and meridional wind) show an overall good resemblance to the global reanalysis, especially for summer. Low-level features like the warm season Great Plains low-level jet are well represented in the simulations. The analysis of the annual mean precipitation and its variance reveals that the ensemble simulations reproduce many of the observed features of the University of Delaware high-resolution (0.5 x 0.5 degree) global rain gauge dataset.

The strong similarity of the ensemble mean and observed variances shows that the regional climate variability is well reproduced in ensemble integrations. Signal-to-noise ratios are larger than 1.5 (that corresponds to ~0.6 - 0.7 correlation coefficient) over a major part of the U.S., especially over the Midwest and also over the mountainous regions like the Rockies and the Appalachians, suggesting that the orographic forcing is contributing to a larger signal.

The results of the study show that even using limited ensemble integrations with a state-of-the-art SG-GCM is beneficial for reducing the uncertainty of the multiyear regional climate simulation, especially when using finer 60 km regional resolution.

3. Feasibility study on using neural network emulations (Krasnopolsky et al. 2005, Krasnopolsky and Fox-Rabinovitz 2005)

At this stage of the study, the work on model dynamics has not been planned and started yet. However, the work on using neural networks emulations for fast and accurate emulation of model physics is well under way as a part of another research effort. As a result of that effort, the developed methodological framework will be beneficial for development of NN emulations for model dynamics. Two recently published papers contain the description of the methodological framework.

4. Completion of SGMIP-1and the detailed analysis of its results (Fox-Rabinovitz et al 2005)

The climate simulation results obtained with the SGMIP-1 SG-GCMs have shown the maturity of the SG-approach. The high quality of both regional and global simulation products has been obtained. The 12-year (1987-1998) AMIP-type SG-GCM simulations for SGMIP-1 are analyzed in terms of studying: (a) the impact of resolution on efficient/realistic downscaling to mesoscales; (b) intraseasonal-to-interannual regional climate variability; and (c) the quality of the multi-model ensemble. Analysis of SGMIP-1 multi-model ensemble

integrations confirmed that a significant reduction of the uncertainty of regional climate simulations is achieved for the multi-model ensemble mean.

More specifically, this is what has been learned from SGMIP-1: (a) the appropriate moderate stretching design for long-term climate simulations is defined, (b) the SG-approach works well and is robust for SG-GCMs with different dynamics and physics; namely, for dynamics using spectral and grid-point schemes, with spherical and geodesical grids, and for physics calculated at intermediate uniform or variable resolution; (c) the SGMIP-1 SG-GCMs provide high quality regional and global climate simulation products, with the differences between the models documented by producing the Taylor diagrams; and (d) the advantage of using the multi-model ensemble (MME) mode has been demonstrated, in the sense that the MME is closer to observations than the individual ensemble members, however, larger regional ensembles are desirable especially for including the impact of better resolved land-sea differences.

The major SGMIP-1 results are as follows.

(a) The efficient regional downscaling to realistic mesoscales is obtained with small/limited regional biases that are a fraction (~25% - 50%) of observational errors, just as a reference. Biases are larger, twice the observational errors, only for the South polar domain (for SGs with the North American area of interest).

(b) Intraseasonal and interannual variability is well represented, namely annual cycles, seasonal differences, time series, variances/standard deviations are close to those of observations or reanalyses.

(c) Orographically induced precipitation and other simulation products are well simulated at meso- and larger scales due to high-resolution regional forcing, for example, the Rockies, the Appalachian and coastal precipitation.

(d) High quality simulation of the 1993 Midwest flood has been obtained (six and a half years after the beginning of the simulation); it points toward the high predictability of the anomalous summer precipitation event.

5. Initiation of SGMIP-2

SGMIP-2 has already begun. The SciDAC ORNL supercomputers are used for the U.S. model simulations.

SGMIP-1 laid a solid scientific foundation for conducting the new SGMIP-2 (phase-2 of SGMIP), with processing and analysis of data obtained with both enhanced uniform and variable resolution SG-GCMs. SGMIP-2 will include the multi-model ensemble simulation results for the extended period of over two decades. The strong coordinated international SGMIP-2 effort, with the accompanying comparisons of enhanced uniform and variable resolution GCMs, will put us in a favorable position for a comprehensive investigation on the diversified impacts on climate simulations due to enhanced global and/or regional model resolution, including the multi-model ensemble results.

The major SGMIP-2 effort will include performing the experiments with the following versions of participation models: (a) SG-GCMs with the prime area of interest over the major part of North America; (b) uniform intermediate resolution GCMs, with the same number of global grid points as in the stretched grids; (c) uniform high resolution GCMs, with the same global resolution as that over the region of interest for the stretched grids. These SGMIP-2 experiments will provide the possibility for a comprehensive analysis of enhanced variable and uniform resolution GCMs and their unique high resolution ensembles against observations.

SGMIP-2 (phase-2) has been endorsed by the WMO/WCRP/WGNE.

6. Atmospheric chemistry experiments (Allen et al. 2004, Park et al. 2004)

Meteorological fields from the GEOS SG-DAS have been used to drive an off-line Stretched-Grid Chemical Transport Model (SG-CTM) at the University of Maryland. Within this reporting period, we published two articles that illustrated the sensitivity of pollutant export from continental boundary layers to model resolution. The first study (Park et al. 2004) focused on the central U.S. during June. For the period of interest, we found that net ozone production in the polluted boundary layer is ~15% less in the mesoscale region of the stretched-grid simulation than in the same area of the coarser resolution simulation due to less artificial dilution of ozone precursors. The net ozone production in convective outflow plumes was also smaller. The second study (Allen et al. 2004) focused on the magnitude of CO sources and pollutant export from Asia. We found that that the export of Asian biomass burning emissions to the Pacific is sensitive to model resolution (it is larger at a finer resolution) and is difficult to quantify through comparison of TRACE-P measurements and model output. These results demonstrate that the effect of regional pollution on the global atmosphere cannot be accurately estimated unless the sensitivity of results to model resolution is considered.

7. SGMIP web site

The SGMIP-1 web site (http://essic.umd.edu/~foxrab/sgmip.html) has been developed following the AMIP-type protocol. It contains spatial and temporal climate diagnostics as well as the Taylor diagrams for the participating models, for both global and regional domains. The major emphasis is on the analysis of the multi-model ensemble means that are overall closer to observations than the individual ensemble members.

Journal papers:

1. Fox-Rabinovitz, M. S., E. H. Berbery, L.L. Takacs, and R.C. Govindaraju, 2005: A multiyear ensemble simulation of the U.S. climate with a stretched-grid general circulation model, *Mon. Wea. Rev.*, will appear in June or July (the page proof is submitted).
2. Fox-Rabinovitz, M.S., J. Cote, M. Deque, B. Dugas, J. McGregor, 2005: Variable-Resolution GCMs: International Stretched-Grid Model Intercomparison Project (SGMIP), to be submitted.
3. Park, R. J., K. E. Pickering, D. J. Allen, G. L. Stenchikov, M. S. Fox-Rabinovitz, 2004: Global simulation of tropospheric ozone using the University of Maryland Chemical Transport Model (UMD-CTM) 1. Model description and evaluation, *J. Geophys. Res.*, **109**, D09301, doi:10.1029/2003JD004266.
4. Park, R. J., K. E. Pickering, D. J. Allen, G. L. Stenchikov, and M.S. Fox-Rabinovitz, 2004: "Global simulation of tropospheric ozone using the University of Maryland Chemical Transport Model (UMD-CTM): 2. Regional downscaling of transport and chemistry over the Central United States". J. Geophys. Res., v. 109, D09303.
5. Allen, D. J., K. E. Pickering, and M. Fox-Rabinovitz, 2004: Evaluation of pollutant outflow and CO sources during TRACE-P using model-calculated, aircraft-based, and MOPITT-derived CO concentrations, J. Geophys. Res., vol. 109, D15S03, doi:10.1029/2003JD2003004250.

Other relevant journal papers:

1. Krasnopolsky, V.M., M.S. Fox-Rabinovitz, and D.V. Chalikov, 2005: "New Approach to Calculation of Atmospheric Model Physics: Accurate and Fast Neural Network Emulation of Long Wave Radiation in a Climate Model", *Mon. Wea. Rev.*, vol. 133, No. 5, pp. 1370-1383.
2. Krasnopolsky, V.M., and M.S. Fox-Rabinovitz, 2005: A New Synergetic Paradigm in Environmental Numerical Modeling: Hybrid Models Combining Deterministic and Machine Learning Components, Environmental Modeling, in press.

Presentations:

1. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, J. McGregor, 2004: International SGMIP: Results of the phase-1 and the design of the phase-2, invited report, WMO/WCRP/WGNE Meeting, 11-15 October, 2004, Exeter, UK.

2. Fox-Rabinovitz, M.S., 2004: Decadal Climate Studies with Enhanced Variable and Uniform Resolution GCMs Using Advanced Numerical Techniques: International Stretched-Grid Model Intercomparison Project (SGMIP), DOE-CCPP PI Meeting, 18-20 October 2004, Seattle, WA.

3. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, J. McGregor, 2004: Regional Climate Modeling with Variable-Resolution Stretched-Grid GCMs, 2004: International Stretched-Grid Model Intercomparison Project (SGMIP), AGU Fall Meeting, Conference on Regional Climate Modeling (invited talk), December 13-17, 2004, San Francisco, CA.

4. Fox-Rabinovitz M.S., J. Cote, M. Deque, B. Dugas, and J. McGregor, 2004: Variable Resolution GCMs: Preliminary Results of International SGMIP (Stretched-Grid Model Intercomparison Project), invited keynote presentation, WCRP-sponsored Regional-Scale Climate Modeling Workshop on High-resolution Climate Modeling: Assessment, added value and applications, Lund, Sweden, March 29-April 2, 2004.