<u>Final Progress Report submitted via the DOE Energy Link (E-Link) in June 2009</u>

Title: **Collaborative Research: Decadal-to-Centennial Climate & Climate Change Studies with Enhanced Variable and Uniform Resolution GCMs Using Advanced Numerical Techniques**
and the 1-year (FY08) Renewal Project Title: **Collaborative Research: Decadal Climate Studies with Enhanced Variable and Uniform Resolution GCMs Using the SGMIP-2 Products**

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Other international participants: Michel Deque (Meteo-France) and J. McGregor (CSIRO, Australia).

Project endorsements: WMO/WCRP/WGNE at its annual meetings in 2004-2008.

Summary

The joint U.S-Canadian project has been devoted to: (a) decadal climate studies using developed state-of-the-art GCMs (General Circulation Models) with enhanced variable and uniform resolution; (b) development and implementation of advanced numerical techniques; (c) research in parallel computing and associated numerical methods; (d) atmospheric chemistry experiments related to climate issues; (e) validation of regional climate modeling strategies for nested- and stretched-grid models. The variable-resolution stretched-grid (SG) GCMs produce accurate and cost-efficient regional climate simulations with mesoscale resolution. The advantage of the stretched grid approach is that it allows us to preserve the high quality of both global and regional circulations while providing consistent interactions between global and regional scales and phenomena. The major accomplishment for the project has been the successful international SGMIP-1 and SGMIP-2 (Stretched-Grid Model Intercomparison Project, phase-1 and phase-2) based on this research developments and activities. The SGMIP provides unique high-resolution regional and global multi-model ensembles beneficial for regional climate modeling and broader modeling community. The U.S SGMIP simulations have been produced using SciDAC ORNL supercomputers. The results of the successful SGMIP multi-model

ensemble simulations of the U.S. climate are available at the SGMIP web site (*http://essic.umd.edu/~foxrab/sgmip.html*) and through the link to the WMO/WCRP/WGNE web site: *http://collaboration.cmc.ec.gc.ca/science/wgne*.

Collaborations with other international participants M. Deque (Meteo-France) and J. McGregor (CSIRO, Australia) and their centers and groups have been beneficial for the strong joint effort, especially for the SGMIP activities.

The WMO/WCRP/WGNE endorsed the SGMIP activities in 2004-2008.

This project reflects a trend in the modeling and broader communities to move towards regional and sub-regional assessments and applications important for the U.S. and Canadian public, business and policy decision makers, as well as for international collaborations on regional, and especially climate related issues.

This final progress report summarizes the results the joint U.S.-Canadian project.

Variable-resolution GCMs using a global stretched-grid (SG) with enhanced resolution over the region(s) of interest constitute an established and cost-efficient approach to regional climate modeling providing an efficient means for regional down-scaling to mesoscales. This approach has been used since the early-mid 90s by the French, U.S., Canadian, Australian and other climate modeling groups along with, or as an alternative to, the current widely-used nested-grid approach. Stretched-grid GCMs are used for continuous climate simulations as usual GCMs, with the only difference that variable-resolution grids are used instead of more traditional uniform grids. 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, stretched-grid GCMs provide self-consistent interactions between global and regional scales of motion and their associated phenomena while a high quality of global circulation is preserved, as in uniform-grid GCMs.

This project has been dedicated 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 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 has been devoted to a comprehensive analysis of decadal climate simulation products of the international SGMIP (Stretched-Grid Model Intercomparison Project), which was initiated and conducted by the P.I.s and other project investigators. It allowed us to fulfill our international SGMIP obligations.

Specifically, the research concentrated on studying decadal climate variability and predictability at meso- and larger scales, with an emphasis on exploring the wealth of information of the SGMIP MMEs (multi-model ensembles) products.

The following major issues have been addressed in this study: (a) the impact of enhanced resolution on producing consistent global and regional fields at meso- and larger scales and their impact on regional events 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.

During the report period the international SGMIP-1 (phase-1) and SGMIP-2 (phase-2) products have been analyzed and the results have been described in a joint papers by the SGMIP-2 participants (Fox-Rabinovitz et al. 2006, 2008). SGMIP has been aimed at in-depth studying the established SG-approach to regional climate modeling.

The strong coordinated international SGMIP effort involving the U.S., Canadian, French and Australian collaborators led by M. Fox-Rabinovitz, J. Cote, M. Deque, and J. McGregor, allowed us to conduct a comprehensive investigation of the diversified impacts on regional climate simulations due to enhanced regional resolution, including the multi-model ensemble results.

The SGMIP-1 includes simulations for the 12-year period (1987-1998) produced with SG-GCMs as well as with intermediate uniform-grid (UG)-GCMs. The SGMIP-2 includes simulations for the extended 25-year period (1979-2003) produced with SG-GCMs as well as with intermediate and high-resolution uniform-grid (UG)-GCMs. It provides unique enhanced variable and uniform resolution multi-model regional and global ensembles beneficial for climate modeling community. In addition to the U.S. prime area of interest, the additional area of interest over Europe has been introduced for SGMIP-2.

The international SGMIP effort has contributed 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.

SGMIP was endorsed by WMO/WCRP/WGNE at its annual meetings in 2004-2008.

The U.S. component

The following is a detailed description of the obtained results.

1. **Development and further improvement of model dynamics with advanced numerical techniques (Baer, Tribbia and Taylor)**

In the companion DOE CCPP study, Co-I.s F. Baer, J. Tribbia and also M. Taylor and H. Wang developed a spectral element dynamical core, denoted SEAM (Spectral Element Atmospheric Model), for a global climate model that they tested thoroughly and subsequently coupled to the NCAR CAM physics and the NCAR CAM land surface model. This model was run in a 20-year AMIP mode using the identical conditions to the AMIP CAM-2 run. That experiment was a success and the model is now available for additional experimentation.

Concurrently the developers included a procedure equivalent to SG using LMR, and performed successful experiments using increased resolution over North America (Baer et al., 2006).

In an independent study, members of the NCAR SCD division developed an upgraded version of SEAM incorporating a semi-implicit time integration. That model called HOMME (High Order Method Modeling Environment) is in the public domain (available over the web) and will be considered as a replacement of SEAM in the coupled spectral element climate model.

2. **Feasibility study on using neural network emulations (Krasnopolsky and Fox-Rabinovitz)**

The work on using neural networks emulations for a fast and accurate emulation of the most time consuming model physics (the radiation block) is a part of another research effort. This innovative approach to treatment of model components using statistical learning techniques (SLT) such as neural networks (NN) is relevant to this study in the following ways. First, speeding-up model calculations is relevant to major CCPP and SciDAC goals. Second, the possibility of the treatment of model physics for SG-GCMs on a uniform fine resolution global grid seems to have some evident advantages and is computationally feasible only when using SLT/NN emulations. Finally, SLT/NN can be used for speeding-up other computational "bottlenecks" including those of model dynamics.

The developed SLT/NN methodological framework is relevant to the above specific applications to SG-GCMs.

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

Multiyear (1987-1997) ensemble integrations using the U.S. SG-GCM, developed and experimented with by the participants, have been employed for U. S. regional climate simulations. The ensemble integrations have been analyzed in terms of climate variability and predictability by Fox-Rabinovitz et al. (2005). The regional spectral analysis, using the technique developed by the Canadian participants, has been applied. The impact of the diurnal cycle on mesoscale circulations has been investigated as well.

4. **Atmospheric chemistry experiments (Allen, Pickering, Stenchikov, Park, and Fox-Rabinovitz)**

The atmospheric chemistry experiments with the model driven by the SG-GCM products have been performed and the results presented by Allen 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.

The study estimated the magnitude of CO sources and pollutant export from Asia and focused on the comparison of TRACE-P measurements and model output.

For another effort, the quality of temporal information from daily burned area inputs was evaluated using transport and chemistry experiments. Carbon monoxide (CO) emissions from boreal forest fires were estimated using burned area inputs with daily resolution. Averaging of emissions data to create 30-day aggregate data reduced the variance by 80%, indicating a substantial loss of information.

Daily data as well as 7-day and 30-day aggregates were used as input to the SG-UMD-CTM (stretched grid University of Maryland Atmospheric Chemistry and Transport Model), and output was compared with CO observations. Model simulations using daily and 7-day average sources agreed better with observations than 30-day average sources.

5. SGMIP-1 experiments and their analysis (Fox-Rabinovitz et al. 2006)

The international SGMIP-1 with participations of the major centers and groups from the U.S., Canada, France, and Australia, has been successfully completed in 2005. 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. 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. (Fig. 1). The U.S. SG-GCM was run on the terra-scale SciDAC supercomputers at ORNL and NERSC. The results of the 12-year (1987-1998) SGMIP-1 multi-model ensemble simulations of the U.S. and global climate 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 laid a solid scientific foundation for conducting the follow-up SGMIP-2 (phase-2 of SGMIP).

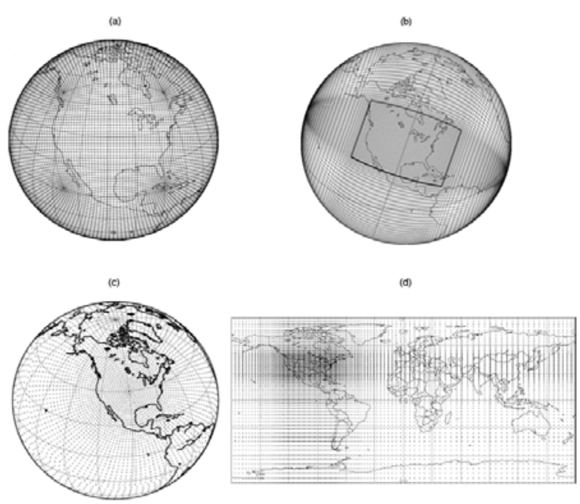

Fig. 1 SGMIP stretched grids with the area of interest over the major part of North America used in the following SG-GCMs: (a) CCAM, CSIRO, Australia; (b) GEM, Environment Canada; (c) ARPEGE, Meteo-France; (d) GEOS, NASA/UMD, U.S. Every other grid-line is shown.

6. SGMIP-2 experiments and their analysis (Fox-Rabinovitz et al. 2008)

SGMIP-2 includes the multi-model ensemble simulation results for the extended period of 25 years (1979-2003). The strong coordinated international SGMIP-2 effort, with the accompanying comparisons of enhanced uniform and variable resolution GCMs, allowed us to conduct a comprehensive investigation on the diversified impacts on climate simulations due to enhanced global and/or regional model resolution, including the unique high uniform and variable resolution multi-model ensemble results.

The major SGMIP-2 effort includes the experiments with the following versions of participating models (C-CAM, Australia, GEM, Canada, ARPEGE, Meteo-France, GEOS, U.S.): (a) SG-GCMs with the prime area of interest over the major part of North America (Fig. 1), and for an additional area of interest over Europe; (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 provided the possibility for a comprehensive analysis of enhanced variable and uniform resolution GCMs and their unique high resolution multi-model ensembles against observations.

The major experiments with four participating GCMs with enhanced regional or global resolution have been performed in 2006-2008. Processing SGMIP-2 results have been done in 2007-2009.

SGMIP-2 products and analysis results are available to WMO/WCRP/WGNE, CLIVAR, GEWEX, IPCC, and to other national and international programs.

SGMIP-2 has been endorsed by the WMO/WCRP/WGNE at its annual meetings in 2004-2008. The SciDAC NERSC supercomputers are used for the U.S. SGMIP simulations.

The major SGMIP-2 conclusions are as follows:

(a) High quality of global simulated products is obtained for SG-GCMs and UG-GCMs.

(b) Regional climate variability for the SGMIP-2 ensembles, in terms of both time mean spatial and temporal prognostic and diagnostic products, are close to those of observations or reanalysis. Seasonal and interannual variability are well represented, namely annual cycles, seasonal differences, time series, and variances/standard deviations are close to those of observations and/or reanalysis.

(c) Over the region of interest: (a) SG-GCMs with $0.5° \times 0.5°$ regional resolution have overall smaller errors, than those of the intermediate ($1° \times 1°$) uniform-grid (UG)-GCMs with the same number of global grid point as for the SG-GCMs; and (b) SG-GCMs and fine ($0.5° \times 0.5°$) resolution UG-GCMs have overall similar errors. The conclusion is illustrated by regional spectra for SG-GCM and fine ($0.5° \times 0.5°$) UG-GCM ensembles which are close to each other and closer to the high-resolution reanalysis NARR (North American Regional Reanalysis) than the spectrum for the intermediate ($1° \times 1°$) UG-GCM ensemble..

(d) The positive impact from enhanced regional resolution on efficient downscaling to realistic mesoscales is obtained. Small regional biases are a fraction (~50% or less) of observational or reanalysis errors), and overall, regional biases are within the uncertainties of available observations and/or reanalysis.
(e) The SGMIP-2 results showed that using a multi-model ensemble for the state-of-the-art SG-GCMs is beneficial for reducing the uncertainty of the multi-decadal regional climate simulation with enhanced regional resolution.
(f) Orographically induced precipitation and other SGMIP-2 prognostic and diagnostic fields (such as temperature, winds, moisture, sea-level pressure, and hydrological cycle components) are well simulated at meso- and larger scales due to high-resolution regional forcing. The major positive regional impact from stretching is obtained from better resolved model dynamics and regionally-enhanced resolution of stationary lower-boundary forcing (orography). In that sense, the improvements are obtained near small-scale terrain features and are reflected, for example, in the Appalachian area precipitation.
(g) SGMIP-2 shows better results than those of SGMIP-1 due to its increased integration period.
(h) The SGMIP-2 products provide the practical possibility of creating joint regional multi-model ensembles for nested- and stretched-grid models which may be beneficial for the national and international regional climate modeling communities.

7. Dissemination of the project results through the project web site (A. Belochitski)

A convenient tool for interactions with researchers, students, and other potential users is the developed SGMIP website (http://essic.umd.edu/~foxrab/sgmip.html). It is used for dissemination of the project information to a broader modeling community. SGMIP information is also available through the link to the WMO/WCRP/WGNE web site: ***http://collaboration.cmc.ec.gc.ca/science/wgne*.**

This detailed project information facilitates the outreach to a broader modeling community and makes the SGMIP products and analysis results available on demand to national and international programs and groups such as DOE CCPP, WMO/WCRP/WGNE, CLIVAR, and IPCC.

An important component of our project has been training a Ph.D. students and post-docs in the area of regional climate modeling with variable-resolution GCMs.

Collaboration with the Canadian partners/groups at the University of Quebec at Montreal (UQAM) and Meteorological Service of Canada (MSC)/RPN has been 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).

During the project period, a joint effort with the Canadian collaborators, we had a productive exchange of the advanced numerical techniques including the updated regional spectral analysis technique and the corresponding software package, and the methodologies of validation for the SGMIP products.

The Canadian component

This study has been devoted to: (a) research in parallel computing and numerical methods; (b) atmospheric chemistry related to climate issues; (c) validation of regional climate modeling strategies for nested- and stretched-grid models; (d) decadal time-scale investigation with the Global Environmental (GEM) model; (e) the limited-area version of GEM model experiments with the same regional resolution.

This project reflects a trend in the modeling and broader communities to move towards regional and sub-regional assessments and applications important for the U.S. and Canadian public, business and policy decision makers, as well as for international collaborations on regional, and especially climate related issues.

This study has been done in collaboration with M. Fox-Rabinovitz et al. of the University of Maryland and with other U.S. investigators.

1. Research in parallel computing and numerical methods (Cote, Gander, Laayouni, Loisel, Qaddouri)

Work has been devoted to the development of new model based on the Yin-Yang grid. This is a composite grid that is singularity free and has quasi-uniform grid spacing. It is composed of two identical latitude/longitude orthogonal grid panels that are combined to cover the sphere with partial overlap on their boundaries. It is suitable for high-performance parallel computing and can be generalized to more than two domains. The non-linear shallow-water model using the two-time-level fully implicit semi-Lagrangian method is composed of two building blocks: the semi-Lagrangian advection and the solution of an elliptic boundary value problem. It was shown as preliminary results that the semi-Lagrangian scheme already validated for a global latitude-longitude grid can be implemented, with minor changes for the Yin-Yang grid. The elliptic boundary value problem is solved by the Schur complement method where the interface problem is solved by GMRES. Other methods known as optimized Schwarz methods are also used in order to increase the performance of the elliptic solver. In these methods the Dirichlet inter-domains transmission condition is replaced by either Robin or second-order transmission conditions with optimized coefficients. The shallow-water equations are solved on this grid with the same algorithm as in the GEM model plus an iterative method for joining the two panels of the grid.

Comparison of the results of a linear shallow-water model discretized on the Yin-Yang grid with the finite-difference method and on the global latitude/longitude Gaussian grid with the spectral method show clearly that the Yin-Yang grid eliminates the pole problem. These results were presented at the Workshop on the Solution of Partial Differential Equations on the Sphere 2006 and 2007 and the 17th International Conference on Domain Decomposition methods (DD17). We have presented the results of a comprehensive set of test cases from a complete shallow-water model at the Workshop on the Solution of Partial Differential Equations on the Sphere in April 2009.

2. **International Stretched Grid Model Intercomparison Project (SGMIP) (Cote, Dugas, Winger)**

The Global Environmental Multiscale (GEM) model has been used operationally by the Canadian Meteorological Centre to produce short- and medium-range forecasts; more recently the GEM model began to be applied for seasonal forecasts. The GEM model has been routinely run in climate mode as a validation tool, differences between the model's climate and that derived from recent re-analysis experiments provide useful indications of GEM's strengths and deficiencies. The model physics configuration closely resembles that of the high-resolution operational global model that was implemented in 2006.

We have completed the first the international SGMIP with the GEM model. The results were compared to the Atmospheric Model Intercomparison Project 2 (AMIP2) uniform global simulation of the same model. SGMIP-1 had a maximum resolution of 0.45 deg. over North-America, while AMIP2 was performed at 1.5 deg. The AMIP2 and SGMIP-1 global climates turn out to be very similar but the differences between the two can be usually traced to the increased resolution over North America. The SGMIP-2 has been also completed. This work has been the subject of several presentations and the papers by Fox-Rabinovitz et al. (2006, 2008) are describing results of the international SGMIP-1 and SGMIP-2 experiments.

Two sets of three 26-year high-resolution climate simulations have been completed and their monthly data have been sent to our University of Maryland colleagues to be compared with that of the other SGMIP2 participants. The first set of integrations saw a climatological annual cycle of sea surface temperatures and sea-ice fractions, while the second set was forced by historically varying monthly mean sea-surface conditions as prescribed by the Atmospheric Model Intercomparison Project 2 (AMIP2) experimental protocol. Two of these six GEM SGMIP simulations were configured with a 0.5 degree high-resolution core area over North-America and two with a 0.5 degree core area over Europe. The last two simulations contributed to the SGMIP2 effort are the corresponding 1 degree global uniform resolution controls. All of these simulations have roughly the same large number of degrees of freedom in the horizontal domain and the same vertical setup. The model’s set of physical parameterizations is the same in all simulations.

The major conclusions are presented above in the U.S. component.

3. **Next-generation CRCM based on GEM-LAM dynamical core and climate and regional climate applications with GEM (Caya, Cote, Dugas, Laprise, Winger, Zadra)**

The Limited-Area Model (LAM) version of GEM is being developed as the next generation Canadian Regional Climate Model. This model is fully parallelized and is linked to a library of extensive physical parameterizations. An invited outreach article has been published in a special issue of “Physics in Canada” devoted to high-performance computing.

This version of GEM has been used to extend locally the SGMIP-2 experiment. Two 26-years GEM-LAM 0.5 deg. horizontal resolution simulations have been completed, their domains reproducing the North-American and European high-resolution core areas of the GEM SGMIP-2 simulations for the same time period. The lateral boundary conditions for these GEM-LAM experiments were provided by another 1.5 deg. global uniform resolution GEM simulation. The LAM and SGMIP show similar surface results. We have also compared the regional climate simulations produced with two limited-area models, GEM-LAM and the Canadian Regional Climate Model (CRCM) of the Ouranos consortium and a 45-year GEM-LAM simulation driven by lateral boundary conditions from the ERA40 re-analysis data.

Results of studies using either the variable-resolution GEM model or its limited-area version (GEM-LAM) have been presented at the recent 1st Workshop of the Canadian Regional Climate Model and Diagnostics (CRCMD) Network. These studies involved graduate students and some of these exploit the variable resolution run made for SGMIP2.

4. Internal variability of RCM in ensemble simulations (Caya, de Elia, Laprise)

The sensitivity of simulated fields of RCMs to a small perturbation to the initial conditions (IC), usually called internal variability, is partially controlled by the lateral boundary forcing, and hence size and geographical location of the integration domain play an important role. Internal variability of RCMs is in general smaller than that of GCMs. It is important to evaluate the internal variability of the RCMs, because it can mask physically forced signals and hence disturb the assessment of climate sensitivity to forcing. The results are published by Alexandru et al. (2007). It was shown that in convective areas (e.g., south of the US), large quantities of precipitation induce important differences between the simulations. Furthermore, it was noticed that the geopotential spread is maximized to the northeast of the domain, region abundant in extra-tropical cyclones. Evaluation of time evolution of synoptic patterns suggests that the maximum in precipitation and geopotential are linked: the former being the trigger of a perturbation that develops in cyclonic circulations and attains the maximal spread before leaving the domain.

5. Big-Brother Experiment with CRCM (Caya, de Elia, Laprise)

The ability of a regional climate model (RCM) to successfully reproduce the fine-scale features of a regional climate is evaluated using an approach nick-named the “Big-Brother Experiment” (BBE). Several studies using the BBE protocol were conducted to assess the various sources of uncertainty in the nesting process of the CRCM (season, temporal resolution, and spatial resolution). These experiments are summarized in the review paper by Laprise 2008 on “Regional climate modeling” in J. Comp. Phys. In general, the Little-Brother succeeds to reproduce rather well the climate statistics of the Big-Brother for all simulated field, for both large and small scales, and for stationary and transient eddies. These results are comforting in that they indicate dynamical downscaling skill for a RCM driven by low-resolution fields for the case in which the large scale are perfect. The Imperfect Big Brother Experiment (IBBE) was designed to study the effect of error in the large scales of the LBCs. The study of Diaconescu et al. (2006) with the IBBE for the summer season over an Eastern North American domain indicate that the RCM is rather neutral to LBC errors: large scale errors are not amplified nor reduced by the RCM. The RCM simulation of small scales is overall poorer in the presence of large scale-errors. An exception is in the case of strong localized forcing, which can accurately recreate part of the small scales.

6. Chemistry related to climate (Cote, Qaddouri, Mahidjiba, Plummer)

The objective of this work has been aimed at obtaining an interactive and conserving semi-Lagrangian scheme for 3D chemistry-atmosphere models. Part of that objective has been reached by coupling a mass-conserving semi-Lagrangian transport scheme to a shallow-water model. In the first part of this study, known classical cases of passive advection in Cartesian geometry with both unstaggered (A-Grid) and staggered (C-Grid) grids were reproduced. A series of validation experiments were performed for 1D and 2D passive advection. These experiments have been done using idealized flows with known analytical solutions. Results obtained are found to be in good agreement with analytical solutions and numerical results available in the literature. In the second part, a series of 2D validation experiments were performed for linear and non-linear shallow-water equations using realistic initial conditions. Results obtained are also found to be in excellent agreement with analytical solution (linear model) and numerical results available in the literature for the non-linear case. Finally, results were obtained for the rotating nonlinear shallow-water equations with conservative passive scalar transport. These results are compared with those obtained with both Eulerian and classical standard interpolation semi-Lagrangian methods (Mahidjiba et al 2008). Work is being pursued on this topic.

Work was also done on the development and integration of chemistry-related modules, most recently a parameterization of lightning-produced NOx, with the Canadian Climate Centre package of physical parameterizations. These have been tested in the Canadian GCM for eventual transfer to the Canadian Regional Climate model, both of which share, more or less, a common physics package.

Project Publications, Presentations and Reports

The U.S. component

Journal papers:

1. Fox-Rabinovitz, M., J. Cote, B. Dugas, M. Deque, and J. L. McGregor, and A. Belochitski, 2008: Stretched-Grid Model Intercomparison Project: Decadal Regional Climate Simulations with Enhanced Variable and Uniform-Resolution GCMs, Meteorology and Atmospheric Physics, Springer, Wien, 14.08.2008, vol. 100, no. 1, pp. 159-178.
2. Fox-Rabinovitz, M.S., J. Cote, M. Deque, B. Dugas, and J. McGregor, 2006: Variable-Resolution GCMs: International Stretched-Grid Model Intercomparison Project (SGMIP), J. Geophys. Res., 111, D16104, doi:10.1029/2005JD006520.
3. 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., Vol. 133, No. 9, pages 2505–2525.
4. 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., 109, doi:10.1029/2003JD2003004250

5. 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.
6. 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.

Journal paper of the companion study (led by Co-I.s, F. Baer and J. Tribbia)

7. Baer, F., H. Wang, J. Tribbia, and A. Fournier, 2006: Climate Modeling with Spectral Elements. Mon. Wea. Rev., Vol. 134, No. 12, pages 3610–3624

Other relevant journal papers:

8. 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.
9. Krasnopolsky, V. M., and M. S. Fox-Rabinovitz, 2006a: A New Synergetic Paradigm in Environmental Numerical Modeling: Hybrid Models Combining Deterministic and Machine Learning Components, Ecological Modeling, 191, pp. 5–18.
10. Krasnopolsky, V. M., and M. S. Fox-Rabinovitz, 2006b: Complex hybrid models combining deterministic and machine learning components for numerical climate modeling and weather prediction, Neural Networks, 19, 122–134.

Presentations and Reports:

WMO/WCRP/WGNE Reports (Blue Book)

1. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, J. McGregor, and A. Belochitski, 2008: SGMIP-2 (Stretched-Grid Model Intercomparison Project): Decadal Regional Climate Simulations with Enhanced Variable and Uniform-Resolution GCMs, WMO/WCRP/WGNE, Research Activities in Atmospheric and Oceanic Modelling, 38, WMO/TD 1467, J. Cote, Ed., 3.5-3.6.
2. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, J.L. McGregor, 2007: Initial results of the SGMIP-2 (Stretched-Grid Model Intercomparison Project, phase-2), WMO/WCRP/WGNE, Research Activities in Atmospheric and Oceanic Modelling, 37, WMO/TD 1397, J. Cote, Ed., 3.5-3.6.
3. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, J. McGregor, 2006: Regional Modeling with Variable-Resolution GCMs: International SGMIP. WMO/WCRP/WGNE, Research Activities in Atmospheric and Oceanic Modelling, 36, WMO/TD 1347, J. Cote, Ed., 3.7-3.9.
4. Fox-Rabinovitz, M. S., J. Cote, M. Deque, B. Dugas and J. McGregor, 2004: International Stretched Grid Model Intercomparison Project (SGMIP): Initial Results on 12-year

Regional Climate Simulations with Variable-Resolution GCMs. WMO/WCRP/WGNE, Research Activities in Atmospheric and Oceanic Modelling, 34, WMO/TD 1220, J. Cote, Ed., 7.13.

WMO/WCRP/WGNE invited presentations

1. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, and J. McGregor, 2008: SGMIP-2 (Stretched-Grid Model Intercomparison Project, phase-2) and the SG-Tropical Belt Experiment, progress report, WMO/WCRP/WGNE Meeting, Montreal, Canada, November 2008.
2. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, and J. McGregor, 2007: International SGMIP: Results of the phase-1 and the preliminary results of the phase-2, progress report, WMO/WCRP/WGNE Meeting, October 2007.
3. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, and J. McGregor, 2006: International SGMIP: Results of the phase-2 and the plans for the phase-3 (future climate), invited presentation, WMO/WCRP/WGNE Meeting, October 2006, Boulder, CO.
4. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, and J. McGregor, 2005: International SGMIP: Results of the phase-1 and the preliminary results the phase-2, invited presentation, WMO/WCRP/WGNE Meeting, November 2005, St. Petersburg, Russia.
5. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, and 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.

Selected conference presentations:

1. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, J. McGregor, 2006: Regional modeling with variable-resolution GCMs: Stretched-Grid Model Intercomparison Project (SGMIP), 2006 Workshop on the Solution of Partial Differential Equations on the Sphere, June 26-29 2006, Monterey CA.
2. Fox-Rabinovitz, M.S., J. Cote, B. Dugas, M. Deque, J. McGregor, 2006: Variable-Resolution GCMs for Regional Climate Modeling: Stretched-Grid Model Intercomparison Project (SGMIP), AGU Joint Assembly, Conference on Dynamical Regional Climate Modeling, May 22-26, 2006, Baltimore, MD.
3. 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.
4. 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.
5. Fox-Rabinovitz M.S., J. Cote, M. Deque, B. Dugas, and J. McGregor, 2004: International Stretched-Grid Model Intercomparison Project (SGMIP): Initial Results on Exploring the New Approach to Regional Climate Modeling and Prediction, 84th AMS Annual Meeting,

Symposium on Forecasting the Weather and Climate of the Atmosphere and Ocean, 11-15 January, 2004, Seattle, WA.

DOE CCPP selected reports:

1. Fox-Rabinovitz, M.S., 2006: 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, 24-26 April 2006, Cambridge, MA.
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.

The Canadian Component (selected publications not included in the above)

Journal papers:

1. Alexandru, A., R. de Elía and R. Laprise, 2007: Internal variability in regional climate downscaling at the seasonal time scale. Mon. Wea. Rev. 135, 3221-3228.
2. Antic, S., R. Laprise, B. Denis and R. de Elia, 2005: Testing the downscaling ability of a one-way nested regional climate model in regions of complex topography. Clim. Dyn., 26, 305-325.
3. Diaconescu, E. P., R. Laprise and L. Sushama, 2006: The impact of lateral boundary data errors on the simulated climate of a nested regional climate model. Clim. Dyn., 28, 333-350.
4. Dimitrijevic, M., and R. Laprise, 2005: Validation of the nesting technique in an RCM and sensitivity tests to the resolution of the lateral boundary conditions during summer. Clim. Dyn. 25, 555-580.
5. Faucher, M., D. Caya, F. J. Saucier and R. Laprise, 2004: Sensitivity of the CRCM Atmospheric and the Gulf of St. Lawrence Ocean-Ice Models to Each Other. Atmos.-Ocean 42(2), 85-100.
6. Jiao, Y., and D. Caya, 2006: An investigation of the summer precipitation simulated by the Canadian Regional Climate Model. Mon. Wea. Rev. 134, 919-932.
7. Laprise, R., 2008: Regional climate modelling. J. Comp. Phys. (Invited paper), Special issue on “Predicting weather, climate and extreme events”, 227, 3641-3666.
8. Mahidjiba, A., A. Qaddouri and J. Cote, 2008: Application of the Semi-Lagrangian Inherently Conserving and Efficient (SLICE) Transport Method to Divergent Flows on a C Grid, Mon. Wea. Rev. 136, 4850–4866.
9. Plummer, D., D. Caya, H. Cote, A. Frigon, S. Biner, M. Giguere, D. Paquin, R. Harvey and R. De Elia, 2006: Climate and Climate Change over North America as Simulated by the Canadian Regional Climate Model. J. of Climate, 19, 3112-3132.
10. Qaddouri, A., and J. Cote, 2004: Optimization of a direct elliptic boundary value problem solver by the combined use of symmetry and Strassen’s algorithm. Mon. Wea. Rev., 132, 2708-2713.

11. Qaddouri, A., J. Cote, M. Gander and L. Laayouni, 2008: Optimized Schwarz methods with an overset grid for the Shallow-Water Equations: Preliminary results. IMACS Journal of Applied Numerical Mathematics, 58, 459-471.
12. Rinke, A., K. Dethloff, J. J. Cassano, J. H. Christensen, J. A. Curry, P. Du, E. Girard, J.-E. Haugen, D. Jacob, C. G. Jones, M. Køltzow, R. Laprise, A. H. Lynch, S. Pfeifer, M. C. Serreze, M. J. Shaw, M. Tjernstrom, K. Wyser and M. Zagar, 2005: Evaluation of an Ensemble of Arctic regional climate models: Spatiotemporal fields during the SHEBA year. Clim. Dyn. DOI 10.1007/s00382-005-0095-3.
13. Sushama, L., R. Laprise, D. Caya, M. Larocque and M. Slivitzky, 2004: On the Variable-Lag and Variable-Velocity Cell-to-Cell Routing Schemes for Climate Models. Atmos.-Ocean 42(4) 2004, 221–233.
14. Sushama, L., R. Laprise, D. Caya, A. Frigon and M. Slivitzky, 2006: Canadian RCM projected climate change signal and its sensitivity to model biases. Int. J. Climatol. 26, 2141-2159.

Outreach article

15. Zadra, A., D. Caya, J. Cote, B. Dugas, C. Jones, R. Laprise, K. Winger and L.-Ph. Caron, 2008: The next Canadian Regional Climate Model. Physics in Canada 64, No. 2, Apr-Jun (Spring), 75-83, Special Issue on Fast Computing, (invited paper).

Conferences and Workshops:

1. Cote, J., M. J. Gander, L. Laayouni, and S. Loisel, 2005: Comparison of the Dirichlet-Neumann and Optimal Schwarz Method on the Sphere. Domain Decomposition Methods in Science and Engineering XV, Lecture Notes in Computational Science and Engineering, Vol. 40, Barth, Griebel, Keyes, Nieminen, Roose, Schlick, Kornhuber, Hoppe, Periaux, Pironneau, Widlund and Xu (Eds.), Springer, 235-242.
2. Cote, J., M. J. Gander, L. Laayouni, and A. Qaddouri, 2007: Optimized Schwarz methods in spherical geometry with an overset grid system. Domain Decomposition Methods in Science and Engineering XVI, Lecture Notes in Computational Science and Engineering, Vol. 55, Widlund and Keyes (Eds.), Springer, 165-172.
3. Cote, Desgagne, Erfani, Girard, Gravel, Mahidjiba, Plante, Qaddouri, Tanguay, Gramann, Zadra, Dugas, Winger, Brunet, Gander, Laayouni and Loisel, 2004: Research and development around the Global Environmental Multiscale (GEM) Model. Workshop on the Solution of Partial Differential Equations on the Sphere July 20-23, 2004, Yokohama, Japan.
4. Dugas, B., and K. Winger, 2005: Results of present climate simulations performed with the GEM forecast model at RPN. 39th Congress of the Canadian Meteorological and Oceanographic Society, May 31-June 3 2005, Vancouver, Canada.
5. Laayouni, L., 2008: Optimized domain decomposition methods for three-dimensional partial differential equations. Domain Decomposition Methods in Science and Engineering XVII, Lecture Notes in Computational Science and Engineering, Vol. 60, Langer, Discacciati, Keyes, Widlund and Zulehner (Eds.), Springer, 339-346.

6. Loisel, S., M. Gander and J. Cote, 2004: A domain decomposition method that converges in finitely many steps for the Laplacian on the sphere. Workshop on the Solution of Partial Differential Equations on the Sphere July 20-23, 2004, Yokohama, Japan.
7. Mahidjiba A., A. Qaddouri and J. Cote, 2006: Conservative semi-implicit semi-Lagrangian method in a shallow-water model: validation of a mass-conserving passive transport scheme, 2006 Workshop on the Solution of Partial Differential Equations on the Sphere, June 26-29 2006, Monterey CA.
8. Qaddouri A., L. Laayouni, S. Loisel, J. Cote and M. Gander, 2006: Optimized Schwarz methods with the composite Yin-Yang grid for the Shallow-Water Equations, 2006 Workshop on the Solution of Partial Differential Equations on the Sphere, June 26-29 2006, Monterey CA.
9. Qaddouri, A., 2008: Optimized Schwarz method with the Yin-Yang grid for the Shallow-Water Equations. Domain Decomposition Methods in Science and Engineering XVII, Lecture Notes in Computational Science and Engineering, Vol. 60, Langer, Discacciati, Keyes, Widlund and Zulehner (Eds.), Springer, 347-353.
10. Zadra, A., R. Laprise, J. Cote, B. Dugas, D. Caya, and K. Winger 2004: Regional climate simulations produced with the GEM and CRCM models. 5th US DoE-CCPP PI Meeting, 18-20 October, Seattle, WA.
12. WMO/WCRP-sponsored Regional-Scale Climate Modeling Workshop on High-resolution climate modelling: Assessment, added value and applications, Lund, Sweden, 29 March – 2 April 2004. Extended abstract volume, Barring and Laprise, 2005 (Editors), 132 pp. ***(http://www.nateko.lu.se/Elibrary/LeRPG/5/LeRPG5Article.pdf)***
11. Zadra, A., R. Laprise, J. Cote, B. Dugas, D. Caya and K. Winger, 2005: Regional climate simulations produced by the GEM and CRCM models. 39th Congress of the Canadian Meteorological and Oceanographic Society, May 31-June 3 2005, Vancouver, Canada.