VARIABLE-RESOLUTION GCMs

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Contents

Contents (cont.)

Stretched vs. Nested Grid Approach

A Stretched Grid Model

Advantages

NO lateral boundary condition problems (No buffer zone).

The possibility to perform climate simulation with NO updates of boundary (or initial) conditions.

Consistent interactions of regional and global scales.

The possibility to introduce a global mesoscale (hydro- or non-hydrostatic) model with variable resolution.

Using ONE model for autonomous simulations.

A Nested Grid Model

Advantages

Computational efficiency due to regional integration domain.

Using a mesoscale (hydro- or non-hydrostatic regional model.

Stretched vs. Nested Grid Approach(cont.)

A Stretched Grid Model

Disadvantages

An extra computational cost due to the global integration domain.

Limitations on the maximal grid interval and on the local stretching factors.

A Nested Grid Model

Disadvantages

Mathematically incorrect lateral boundary conditions and introduction of a buffer zone to control computational noise.

Using future lateral boundary conditions from an outer model or from data analyses. The latter is an actual "quasi-data assimilation" rather than simulation.

Non-consistent interactions of regional and global scales.

Non-autonomous simulations.

Stretched vs. Nested Grid Approach(cont.)

Notes:

- The major goal for both approaches is achieving an efficient regional DOWN-SCALING.
- An OPTIMAL use of each approach for different applications (NOT an “either-or” situation).
- A possibility of combining both approaches.

Variable-Resolution GCMs

1. RPN/CMC, GEM (Global Environmental Multiscale) model (Cote et al. 1998, 2000)
   - Stretched grid (Staniforth and Mitchell 1978) dynamics with:
     - Grid-point semi-implicit semi-lagrangial scheme.
     - Efficient parallel code on the NEC computer.
     - Extensive experience in short-term forecasting.
   - Major experiments (in progress):
     - High-resolution, 0.5 degree, global AMIP-type 17-year simulation.
     - Regional climate experimentation.

Variable-Resolution GCMs (cont.)

2. Meteo-France, Arpege model
   - Variable-resolution spectral dynamics with: Grid-point semi-implicit semi-lagrangial scheme.
   - The Schmidt (1977) conformal transformation:
     - Stretching from the rotated "pole" point all the way around the globe (no area with uniform resolution); and
     - Using moderate stretching factors for regional climate simulations.
   - Variable-resolution physics:
     - Extensive experience in short-term forecasting (Benard and Yassad 1996, Caian and Geleyn 1997).

Variable-Resolution GCMs(cont.)

2. Meteo-France, Arpege model
   - Major regional climate experiments:
     - European and north Atlantic climate (Deque and Piedelievre 1995, Machehauer et al. 1998, Doblas-Reyes et al. 1998, Deque 2000).
     - European climate change studies (2xco2) (Deque et al. 1998).
     - Asian monsoon (Lorant 2000).
     - Equatorial convection (Lorant and Royer 2001, to appear).

Variable-Resolution GCMs(cont.)

3. Australian CSIRO Model
   - Global conformal-cubic grid (McGregor 1996, McGregor and Dix 1997, 1998);
   - Semi-implicit semi-lagrangial scheme (Mcgregor 1996a,b);
   - Experience in short-term forecasting and typhoon prediction;
   - Regional climate experiments.
4. University of Utah model (Paegle 1989, Paegle et al. 1996)
5. Variable-resolution 2-D spectral model (Hardiker 1997, the FSU group)

Variable-Resolution GCMs(cont.)

6. NCSU variable-resolution non-hydrostatic model (Semazzi's group)

   Dynamical core:

   – Fully compressible system of governing equations
   – Semi-implicit semi-lagrangian discretization
   – Dry adiabatic physics
   – Spherical coordinates, grid point model
   – Hydrostatic/nonhydrostatic switch in the model code
   – Generalized horizontal variable resolution

Variable-Resolution GCMs(cont.)

6. NCSU variable-resolution non-hydrostatic model (Semazzi's group)

   Dynamical core:

   – Experiments:

     - Test cases
     - 1200-day simulations based on Held-Suarez forcing
     - Ultra-high resolution (400 meters) over selected region

Variable-Resolution GCMs (cont.)

GEOS (Goddard Earth Observing System) GCM (the basic model)

- Dynamics: finite-differences: Arakawa and Lamb (1981); Suarez and Takacs (1995); Fox-Rabinovitz et al. (1991);
  - Filters: high latitude fourier; local Shapiro (1970);
  - Resolution:
    - a) 2 x 2.5 degree; 70 layers or
    - b) 1 x 1 degree; 48 layers
  - Radiation: Chou and Suarez (1994)
  - Turbulence/PBL: Helfand and Labraga (1989)
  - Convection: RAS (Relaxed Arakawa-Schubert): Moorthi and Suarez (1992)
  - Land-surface model (LSM): Koster and Suarez (1994)
  - Participation in AMIP

Variable-Resolution GCMs(cont.)

7. GEOS SG-GCM (Fox-Rabinovitz et al. 1997, 2000, 2001, Fox-Rabinovitz 2000)

- Same dynamics and physics as in GEOS GCM:
  - Model dynamics (and orography) is calculated directly on the stretched grid.
  - Model physics is calculated on an intermediate uniform resolution grid.
  - The model integration history resides effectively on the stretched grid.
- Refined/adjusted to variable resolution high latitude (Takacs et al. 1999) and local filters;
- Regional resolution obtained by redistribution of:
  - a) 2 x 2.5 degree global uniform grid to 60 km one the area of interest.
  - b) 1 x 1 degree global uniform grid to 40 km one the area of interest.
  - c) 1 x 1 degree global uniform grid to 40 or 50 km over four areas of interest.

Variable-Resolution GCMs(cont.)

7. GEOS SG-GCM(cont.)

- Major applications:
  - Regional climate simulation. .
  - Simulating products for driving atmospheric chemistry transport models.
  - Simulating products for driving a NOAA/OH/HRL hydrologic model (planned).

Variable-Resolution GCMs(cont.)

Current Research Areas

1. Development of the new GEOS SG-GCM (work in progress):
   - Model dynamics: finite-volume scheme (in collaboration with K. Yeh using Lin and Rood 1996, 1997, Lin 1997).
   - Model physics: the NCAR CCM4 (CAM).
2. Development of the SG-GCM with spectral-element dynamics and the NCAR CCM4/CAM physics (a companion study with F. Baer, J. Tribbia, A. Fournier, and M. Taylor).
3. Continuing simulations with GEOS SG-GCM to study long-term regional climate variability and predictability.

Variable-Resolution GCMs(cont.)

Future Research Areas

(for both variable and uniform high resolution GCMs)

- Developing more flexible/sophisticated SG-generators (planned).
- Developing model physics for mesoscale resolution(a long-term effort).
- Using coupled ocean-atmosphere-land GCMs for long-term predictions (a long-term effort).
- Performing ensemble integrations (planned).
- Developing new GCMs with flow-dependent anisotropic grids for both regional and global simulations (a long-term effort).
- Developing extensive applications: providing forcing products for high resolution atmospheric chemistry, hydrologic, and biosphere models (planned).

GEOS SG-DAS
(Fox-Rabinovitz et al. 2001)

- Incorporates the GEOS SG-GCM
  - Physical space analysis system (PSAS): e.g. Cohn et al. (1998).
  - Incremental analysis update: Bloom et al. (1996).
  - Statistical models and bias correction: e.g. Cohn et al. (1998); Dee (1997).
  - Diabatic initialization (optional): Fox-Rabinovitz (1996); Fox-Rabinovitz et al. (1998).
  - Analyses and diagnostics are produced on:
    a) Sigma-levels, or
    b) 18 mandatory pressure levels from surface to 0.1 hPa.
  - Regional resolution obtained by redistribution of:
    a) 2 x 2.5 degree global uniform grid to 60 km over one area of interest.
    b) 1 x 1 degree global uniform grid to 40 km over one area of interest.
    c) 1 x 1 degree global uniform grid to 40 or 50 km over four areas of interest.

GEOS SG-DAS(cont.)

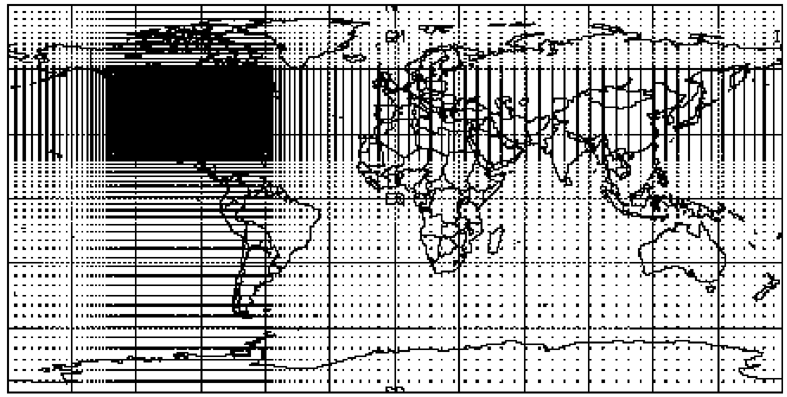
- Major applications.
- Producing analyses and diagnostics for regional climate studies and for SG-GCM validation.
- Producing analyses and diagnostics for driving atmospheric chemistry transport models.
- Producing analyses and diagnostics for driving a hydrologic model (planned).
- New satellite data impact studies (planned).

Variable-resolution grids used and planned to use:

1. Used with finite-difference approximation:
   - Stretched grid with one area of interest.
   - Stretched grid with <u>multiple</u> areas of interest.

2. Will be used with other advanced approximations (finite-volume and spectral element):
   - Enhanced resolution <u>global orography</u>.
   - Global approximations with carefully designed multiple areas of interest variable-resolution anisotropic (boundary- condition-and-flow-dependent) grids

An example of a stretched grid with one area of interest (AOI) with enhanced 60 km regional resolution over the U.S.



A blow-up:

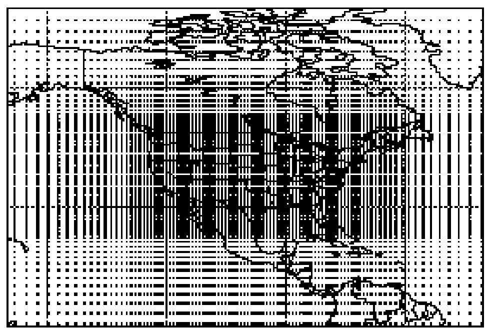
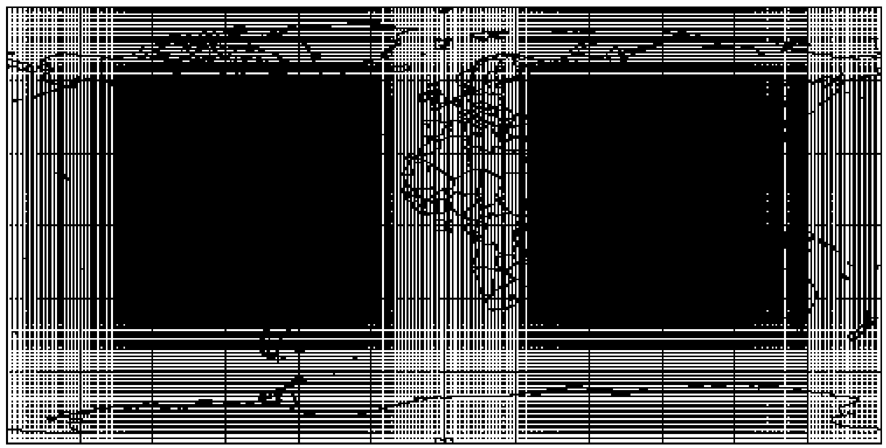


Figure 1. (a) Stretched grid at 60 km

An example of a stretched grid with four areas of interest over:
1.the U.S./Western Atlantic ocean; 2. El Nino area/Brazil-Argentina;
3. India-China; and 4. Eastern Indian ocean/Australia



Stretched grid with maximum resolution over four regions

SG-design

Q: What are optimal/necessary requirements/controls for a SG-design to be imposed for obtaining successful regional climate simulations that would provide:

1. An efficient downscaling over the area(s) of interest;
2. Consistent/realistic interactions between global/large- and regional/meso-scales;
3. A sufficient quality/skill of global circulation.

- Fine uniform resolution over the area(s) of interest.
- Uniform stretching with constant local stretching factors.
- Moderate local stretching factors, within ~5%
- Limited maximum grid intervals, within 2-3 degrees, the resolution of typical GCMs.

SG-design(cont.)

NOTE: The stretched grids obtained under the above conditions have at least an order of magnitude less grid-points than the corresponding global fine resolution (same as that of the area of interest) uniform grids, and therefore, are at least an order of magnitude more computationally efficient.

NOTE: The above conditions make SG-approach a "working compromise" between a relatively poorly resolved flow coming into the area(s) of interest and regional enhanced resolution fields and surface boundary forcing. In other words, the efficient down-scaling is obtained over the area(s) of interest in spite of degradation of skill of the SG-simulation or SG-data assimilation for the areas located far away from the area(s) of interest.

NOTE: A non-moderate/overly aggressive stretching results in the loss of the solution accuracy, and computational dispersion problems (wave trapping/well, wave scattering) (e.g. Vichnevetsky 1987, Fox-Rabinovitz 1988, Gravel and Staniforth 1992, Cote 1997, Caian and Geleyn 1997).

NOTE: At this stage of the model development, the SG-GCMs are designed and applied to regional not global climate simulation (see the further discussion on the future GCMs with anisotropic/flow-dependent grids for both regional and global simulations).

The SG-GCM Modes of Integration

1. Simulation
2. Data Assimilation
3. The special mode of integration is designed to fit the PIRCS (Project to Intercompare Regional Climate Simulations) framework or an imitation of a nested-grid approach.

   - The PIRCS nested-grid models are driven by a lateral boundary condition forcing obtained from the NCEP re-analyses.
   - In our case, the SG-DAS is run withholding all observational data over the area of interest. As a result, boundary information (not boundary conditions that are not needed for the SG-GCM) or SG-DAS analyses are produced outside the area of interest and the SG-GCM is continuously run inside the area of interest.

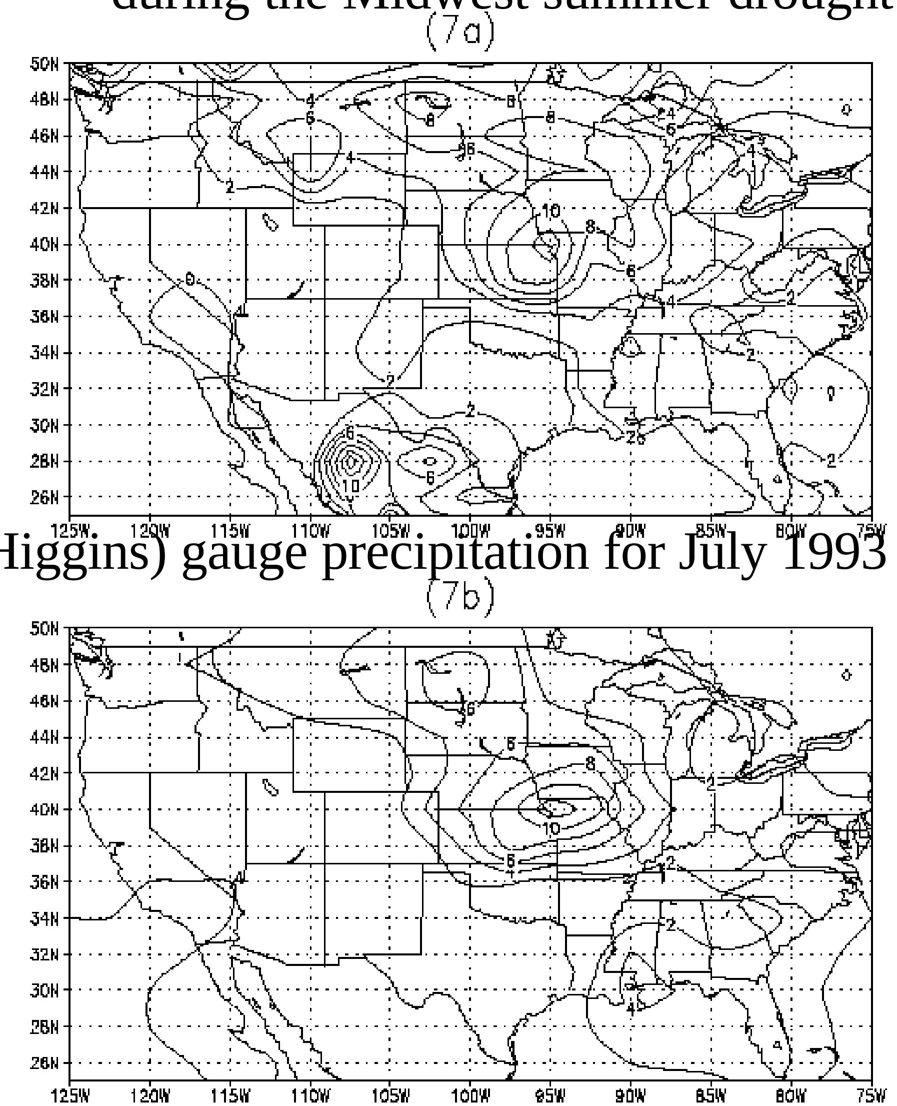
Q: Could <u>mesoscale</u> features be realistically represented in SG-simulation and SG-data assimilation for <u>time-averaged</u> (monthly, seasonal, annual, etc.) fields?

Q: In other words, what kind of <u>mesoscale</u> features would not be smoothed or filtered out by time-averaging for monthly and longer time scales (like the mesoscale features <u>induced by orographic</u> and/or <u>land-sea differences stationary forcing</u>)?

Q: What <u>effective</u> regional resolution is needed for model <u>dynamics</u> and <u>physics</u> for simulating <u>realistic mesoscale</u> features/circulations?

- Comparison/validation of 40, 50 and 60 km SG-GCM simulations against:
  - a) The 50 and 60 km <u>SG-DAS</u> verifying analyses and diagnostics, and
  - b) <u>Independent</u> datasets (not used in the SG-DAS) like gauge precipitation at 0.5 and 0.25, surface temperature at 0.5, and sea winds at 0.25 degree resolution.

SG-GCM (60km) simulated precipitation for July 1993 during the Midwest summer drought

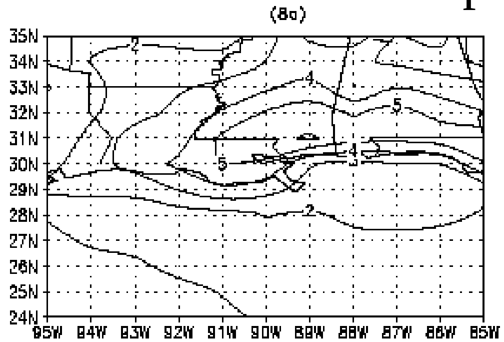


Verifying NCEP (Higgins) gauge precipitation for July 1993 (over the U.S. only)

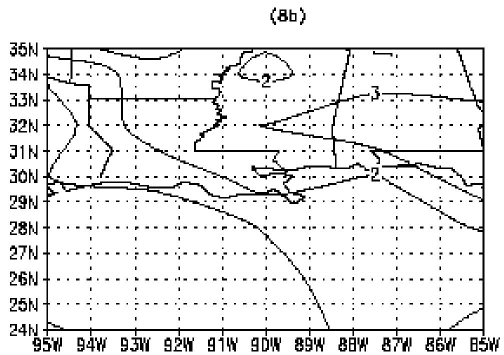
Figure 7a 60Km stretched grid GCM precipitation for July 1993
Figure 7b NCEP gauge (over the U.S) precipitation for July 1993
From: Fox-Rabinovitz, 2000, JGR, Vol. 105, No. D24, pp. 29,635-29,646

From: Fox-Rabinovitz, 2000, JGR, Vol. 105, No. D24, pp. 29635-29646

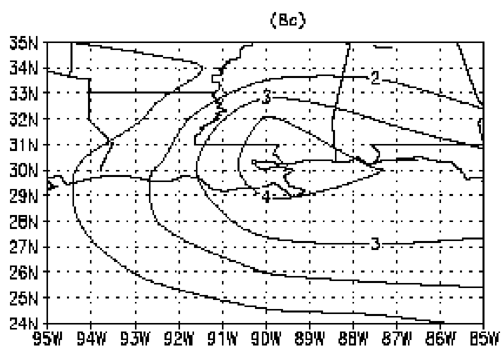
A blow-up over the Gulf states: precipitation for July 1993



SG-GCM (40km): recovered precipitation over the Gulf states



SG-GCM (60km): underestimated precipitation over the Gulf states



Verifying NCEP (Higgins) gauge precipitation

Figure 8a 40Km stretched grid GCM precipitation for July 1993
Figure 8b 60Km stretched grid GCM precipitation for July 1993
Figure 8c NCEP gauge(over the U.S) precipitation for July 1993
From: Fox-Rabinovitz, 2000, JGR, Vol. 105, No. D24, pp. 29,635-29,646

From: Fox-Rabinovitz, 2000, JGR, Vol. 105, No. D24, pp. 29635-29646

From the PIRCS Abstract of a PIRCS talk

(by R. Arritt and 25 co-authors):

"…A "nested-grid imitation" version of a stretched-grid model performs well relative relative to the other models, though the stretched-grid model is not strictly comparable to the limited-area models because of differences in driving data and other factors. The stretched-grid model performs especially well with respect to location (and magnitude, MFR) of the precipitation maximum in the 1993 flood."

From: Arritt's presentation at the Second Workshop on Variable-Resolution Climate Modeling, May 2000, Montreal, Canada

Conclusions

1. Variable resolution SG-GCMs represent a viable approach to regional climate modeling. An efficient regional downscaling is obtained for monthly, seasonal, and multiyear simulations with different variable resolution GCMs.

2. For different variable resolution GCMs, the SG-design with moderate/strictly-controlled parameters has to be used for preserving the high quality of global circulation and for providing consistent/realistic interactions between global/large- and regional/meso- scales. The SG-GCMs are at least an order of magnitude more computational cost-efficient than the global uniform fine resolution grid GCMs (with the same global fine resolution as that over the area(s) of interest for SGs).

3. The successful SG-GCM simulations of the anomalous U.S. summer events, the drought of 1988 and the flood of 1993, are performed. The NAMS and its link to the Midwestern U.S. precipitation are realistically simulated. The positive impact of finer, 40 km vs. 60 km, regional resolution is obtained in terms of representing mesoscales for instantaneous and time-averaged (monthly mean) fields. The 1993 simulation results are submitted to the PIRCS. They compare well with other participating (nested-grid) models.

Conclusions(cont.)

4. The extended 10-year (1988-1998) SG-GCM simulation confirmed that the efficient downscaling to mesoscales is sustained for long-term regional climate simulation and data assimilation. The 10-year mean fields and diagnostics compare well with verifying SG-DAS products and independent observational data (gauge precipitation). It indicates the promising potential of the ensemble integration approach.

5. The new SG-design with multiple areas of interest is developed and implemented. It makes possible studying the major monsoonal circulations over North and South America, India/China, and Australia. This SG-design will be used as a "baseline" for future regional simulations. The results of the 15-month (Sept. 1997- Dec.1998) simulation are preliminary analyzed and found encouraging.

6. The developed SG-DAS incorporating the SG-GCM is capable of producing realistic regional analyses and diagnostics at mesoscales.

Future Plans

1. Performing SG-GCM simulation and SG-DAS analyses and diagnostics for the 1997-1999 (and beyond) ENSO cycle, with 40-50 km and finer regional resolution. Submitting the results to the PIRCS future experiments.

2. Studying potential regional climate connections for the areas of interest that include the major monsoonal circulations.

3. Assessing inter-annual regional climate variability and predictability.

4. Developing and implementing the SG-approach for the new SG-GCMs using advanced numerical techniques and NCAR/CCM4/CAM physics:
   - Finite-volume dynamics (with K. Yeh).
   - Spectral-element dynamics (a companion study with F. Baer, J. Tribbia, A. Fournier).

Future Plans(cont.)

5. A feasibility study on ensemble SG-GCM integrations. Note: The analysis of 10-year mean simulated fields and diagnostics provides positive indications on the potential of the ensemble approach.

6. A feasibility study on using anisotrpic (boundary condition and flow dependent) gradually varying global grids as an alternative to uniform global grids, for both regional and global climate modeling.

7. Proposal on a joint effort on intercomparison of variable resolution stretched grid GCMs.

Proposal on Intercomparison of Variable Resolution GCMs: Stretched-Grid Model Intercomparison (SGMIP)

The variable-resolution GCMs have matured enough to justify the intercomparison effort

1. There are several SG-GCMs with different dynamics and physics used for regional climate simulation and applications. The obtained results have shown the potential of the SG-approach.
2. There are several computational topics that will be addressed by the intercomparison:
    - Different stretching strategies
    - Different approximations of model dynamics, and filters
    - Different model physics including treatment of physics on stretched grids
    - Ensemble calculations
    - Optimal performance on parallel supercomputers

Proposal on Intercomparison of Variable Resolution GCMs(cont.)

3. The 12 year simulation period (1987-1999) including the ENSO cycles is proposed for:
   - Studying the impact of resolution on efficient/realistic downscaling to mesoscales
   - Studying the U.S. anomalous regional climate events (floods, droughts, etc.) and major monsoonal circulations in the context of ENSO cycles at mesoscale resolution
   - Studying the impact surface boundary condition forcing
   - Studying the U.S. water and energy cycles

Proposal on Intercomparison of Variable Resolution GCMs(cont.)

4. The major potential participants have expressed their interest in participating in the project.
   - The potential participants are: Fox-Rabinovitz (UMD and NASA/Goddard), Deque (Meteo-France), Cote and Dugas (RPN/CMC), McGregor (CSIRO), Baer (UMD), Tribbia (NCAR), Fournier (UMD and NCAR).
   - Six SG-GCMs will be included into intercomparison. Other models/participants are welcome.
   - The AMIP representatives (L. Gates and P. Gleckler) have expressed their potential interest in this effort to become in the future a special regional project within AMIP.
   - The proposal was discussed at the meeting on 4/2/01 with 10 people attending (including the above participants) . The consensus was that we have to go ahead with the project. The details and logistics will be discussed and finalized by

     e-mail.
5. The requirements and support for the intercomparison will be specified in 2001 so it could be started in 2002.

Recent Journal Publications on the GEOS SG-GCM

1. Fox-Rabinovitz, M. S., G.L. Stenchikov, M.J. Suarez, and L.L. Takacs, 1997: A Finite-Difference GCM Dynamical Core with a Variable Resolution Stretched Grid. Mon. Wea. Rev.,vol. 125, No. 11, 2943-2968.

2. 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.

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

4. Fox-Rabinovitz, M. S., 2000: Regional climate simulation of the anomalous U.S. summer events using a variable-resolution stretched-grid GCM. J.Geophys Res.(the special issue on Advances in Regional Climate Modeling), Vol. 105 , No. D24 , pp. 29,635-29,646.

Recent Journal Publications on the GEOS SG-GCM

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

6. Fox-Rabinovitz, and E. H. Berbery, 2001: Simulation of the North American Monsoon System and its Link to Midwest Precipitation using a variable resolution stretched grid GCM, to be submitted.

7. Fox-Rabinovitz, M. S., L.L. Takacs, and R.C. Govindaraju, 2001: A Variable Resolution Stretched Grid Data Assimilation System: Regional Analyses and Diagnostics, to be submitted.

8. Takacs, L. L., W. Sawyer, M. J. Suarez, and M. S. Fox-Rabinovitz, 1999: Filtering Techniques on a Stretched Grid GCM, NASA/TM-1999-104606, Vol. 16, 50 pp.

Additional discusion

Q: How could the concept consistent horizontal and vertical resolution by applied to the SG-GCM?

1. SG-GCM Vertical resolution: 70 levels, or 2-3 times more than in a typical GCM or a mesoscale/nested-grid model
2. A gradual vertical re-spacing when approaching the area(s) of interest (not clear, just "a thought in progress")

Additional discussion(cont.)

Implementation of Model Dynamics and Physics

Q: What are the relative merits of increasing spatial resolution versus more accurate or sophisticated physics?

- The first step: increasing regional resolution for model dynamics and orography (as its integral part). Using the existing model physics up to 0.5 degree resolution.

  Using model physics at an intermediate uniform resolution (Lander and Hoskins 1997)
- The second step: increasing intermediate uniform global resolution for model physics and land-sea differences.
- The entire integration history resides effectively on a variable-resolution grid.

Q: What are the impacts of finer regional resolution for model dynamics and orography (as its integral part), and for model physics and land-sea differences?

Additional discussion(cont.)

Regional Resolution and Downscaling

Q: Does the use of higher spatial resolution guarantee or rather may provide more accurate results?

Q: Is there a limit to what spatial resolution could be achieved?

- Computing capabilities.
- Refined model dynamics and physics formulations.
- Variable-resolution strategies preserving efficient regional/sub-regional downscaling properties.
- Consistently resolved components of coupled models.
- Limitations of effective resolution and accuracy for observing systems producing data for:
  - Refined formulation of model physics
  - Surface elevation
  - Continental contours and land-sea differences

Additional discussion(cont.)

Accuracy of Regional Climate Simulations and Impacts of Boundary Forcing

Q: How accurate are variable resolution AGCMs in reproducing the observed high resolution seasonal and annual climate statistics (including extreme events) when driven by: (a) observed surface boundary forcing (SST, sea-ice, soil moisture, and snow), without a LSM; or (b) observed SST and sea-ice, and a LSM (providing soil moisture, and snow)?

Q: What is the impact on regional climate simulations from using a LSM instead of an observed soil moisture and snow?

Additional discussion(cont.)

Q: Is obtaining a monotonic SG-solution enough for obtaining/ guaranteeing an efficient regional downscaling or it is rather a necessary condition for that to take place?

Monotonic Solution vs. Efficient Downscaling

Additional discussion(cont.)

Q: What is an optimal way to represent non-homogeneous/ anisotropic fields?

Uniform grids

vs.

Carefully designed variable-resolution grids for global approximations

(SGs with multiple areas of interest: gradually varying, anisotropic, boundary-condition-and-flow-dependent grids).

Additional discussion(cont.)

Limitations on Regional Resolution

What does limit the spatial resolution of GCMs in the near future?

– For model dynamics:
  - The non-hydrostatic approximation is supposed to be used when increasing regional resolution beyond ~5-10 km.
  - The hydrostatic approximation is used when increasing regional resolution up to 10 km.

– For model physics:
  - The existing parameterizations seem to be applicable when increasing regional resolution up to 40-50 km (and even to 25 km).
  - The existing parameterizations has to be reconsidered for finer regional resolution; some physical processes will be refined/adjusted to mesoscales that will be a new challenge for modelers.

Additional discussion(cont.)

Limitations on Regional Resolution(cont.)

What does limit the spatial resolution of GCMs in the near future?

– For both model dynamics and physics:
  - Providing consistent horizontal and vertical resolution for an adequate representation of 3-D simulated fields.