SIMULATION OF ANOMALOUS REGIONAL CLIMATE EVENTS WITH A VARIABLE RESOLUTION STRETCHED GRID GCM

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Submitted for publication to JGR (the ARCM special section)

(December 1999)

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ABSTRACT

The stretched-grid approach provides an efficient down-scaling and consistent interactions between global and regional scales due to using one variable-resolution model for integrations. It is a workable alternative to the widely used nested-grid approach introduced over a decade ago as a pioneering step in regional climate modeling. A variable-resolution GCM employing a stretched grid, with enhanced resolution over the U.S. as the area of interest, is used for simulating two anomalous regional climate events, the U.S. summer drought of 1988 and flood of 1993. The special mode of integration using a stretched-grid GCM and data assimilation system is developed that allows for imitating the nested-grid framework. The mode is useful for inter-comparison purposes and for underlining the differences between these two approaches.

The 1988 and 1993 integrations are performed for the two month period starting from mid May. Regional resolutions used in most of the experiments is 60 km. The major goal and the result of the study is obtaining the efficient down-scaling over the area of interest. The monthly mean prognostic regional fields for the stretched-grid integrations are remarkably close to those of the verifying analyses. Simulated precipitation patterns are successfully verified against gauge precipitation observations. The impact of finer 40 km regional resolution is investigated for the 1993 integration and an example of recovering subregional precipitation is presented.

The obtained results show that the global variable-resolution stretched-grid approach is a viable candidate for regional and subregional climate studies and applications.

1. Introduction

A variable-resolution GCM using a global stretched grid with fine uniform resolution over the area of interest is an emerging new approach to regional and subregional climate modeling. This approach is being explored as an alternative methodology to the currently widely-used nested-grid approach that represents a pioneering first step toward reliable regional climate simulations (e.g. Dickinson et al. 1989, Pielke et al. 1992, Giorgi 1990,1995, Juang and Kanamitsu 1994). The computational efficiency of the nested-grid approach is high due to using a regional integration domain. There is the possibility of combining the outer hydrostatic GCM or reanalyses and an inner non-hydrostatic model. It is preferable to use the GCM physics for the inner model (e.g. Caya and Laprise 1999). There also exists the possibility of using a perturbation regional model (Juang and Kanamitsu 1994).

The stretched-grid approach is introduced as a new application of global models or GCMs, with enhanced resolution for both prognostic fields and boundary forcing over the area of interest. It also avoids the need to apply damping techniques within a computational buffer region that are required in nested grid models to control severe computational noise arising from the application of lateral boundary conditions. A further advantage of variable-resolution stretched-grid models is that they provide self-consistent interactions between global and regional scales of motion and their associated phenomena.

A general solution for computational problems arising from stretched grid non-uniformity, is to introduce diffusion-type filters and uniform "conservative" stretching, with constant stretching factors that typically deviate no more than 5-10% from unity. These are the necessary tools for controlling different kinds of computational noise (e.g. Staniforth and

Mitchell 1978, Vichnevetšky 1987, Fox-Rabinovitz 1988, Fox-Rabinovitz et al. 1997).

For a grid point model with variable resolution, the stretched grid approach with the same model used over the entire globe, seems to be attractive because it is free of the ill-posed boundary condition problem that arises for nested grids (Oliger and Sundstrom 1978). The associated additional computational cost due to stretching versus nesting, is not overwhelming because a significant part of global grid points are usually located inside the area of interest for many applications (e.g. Cote et al. 1993).

It should be emphasized that the optimal choices between the nested and stretched-grid approaches have to be made for different regional applications. Their combination may appear to be an attractive option as well.

The variable-resolution stretched-grid models have been first developed in the late 70's for the short-term, 24-48 hour, forecasting (Staniforth and Mitchell 1978, Staniforth and Daley 1979). The operational stretched-grid grid-point model is used the short-term forecasting at the Canadian Meteorological Center since the early 90's (Cote et al. 1993, 1998, Cote 1997, Staniforth 1995, 1997). The development of the stretched-grid spectral model was started independently in the late 80's at Meteo-France (Courtier and Geleyn 1988) using the approach developed by Schmidt (1977). The model is used for operational short-term forecasting since the mid-90's (e.g. Yessad and Benard 1996). The first regional climate simulation with encouraging results was performed with the Meteo-France model in the mid-90's (Deque and Piedelievre 1995).

Other variable-resolution models have been developed for regional applications (e.g. Paegle 1989, Hardiker 1997, McGregor and Katzfey 1998).

The Goddard Earth Observing System (GEOS) stretched-grid (SG)-GCM is being developed by the author and his collaborators for regional climate applications since the mid-90's. It was started from employing the dynamical core framework with a Newtonian-type physics (Held and Suarez 1994), for experiments without and with orography (Fox-Rabinovitz et al. 1997, 1999). The computational noise problems due to grid non-uniformity were resolved and a monotonic noise-free solution was obtained. Then the SG-approach was extended to the full diabatic GEOS GCM and the successful straightforward regional climate simulation (with no periodic updating of conditions at the region's boundaries) has been performed for the 1988 U.S. drought (Fox-Rabinovitz et al. 2000).

The SG-GCM has been introduced into the GEOS data assimilation system (DAS) that resulted in development of the stretched-grid version of the system. The GEOS SG-DAS is used in this study in a special simulation mode for imitating a nested-grid framework, and for producing the verifying regional analyses.

Variable-resolution stretched-grid modeling provides a practical and scientifically attractive way of performing cost-effective regional experiments with finer resolution over an area of interest than are likely to be possible in the foreseeable future with fine uniform global grid models. Actually, any GCM resolution can be made at least 2-4 times finer over the area of interest through the SG-approach. Depending on the regional resolution used, the computational savings are at least one order of magnitude compared to computer time needed for the corresponding run with a global uniform fine grid GCM (Cote 1997, Fox-Rabinovitz et al. 1997, 1999).

It is noteworthy that the computational efficiency provided by the stretched-grid approach, is not the only reason or rational for its practical implementation. It is at least equally or even more important that through this approach an efficient down-scaling is obtained that allows for an adequate representation of fine and very fine regional mesoscale fields, diagnostics, and phenomena.

The anomalous regional climate events of the U.S. summer drought of 1988 and flood of 1993 have been chosen for the PIRCS (Project to Intercompare Regional

Climate Simulations). These events are extensively investigated with the variety of nested-grid models as described, for instance, in (Takle et al. 1999). Performing experiments with the SG-approach for these anomalous U.S. climate events is useful for comparison purposes as well as for better understanding of the differences between these two approaches.

The major goal of the study is to estimate the down-scaling and its accuracy for simulations using a variable-resolution approach that allows one to adequately represent the regional scales over the area of interest. In other words, the efficiency of the down-scaling over the area of interest, due to better-resolved regional fields and surface boundary condition forcing, is investigated. It is noteworthy that the investigation is devoted to studying the impact of variable resolution in terms of regional down-scaling for the SG-approach rather than producing the case studies of the events.

A brief descriptions of the SG-GCM and SG-DAS are given in Section 2. The stretched-grid generator and the experimental setup are described in Section 3. The simulation results for regional prognostic fields and precipitation are discussed in Sections 4 and 5, respectively. The conclusions are given in Section 6.

2. A brief description of the SG-GCM and SG-DAS

The GEOS GCM was developed by the Data Assimilation Office (DAO) at the NASA Goddard Laboratory for Atmospheres. The earliest predecessor of the GEOS GCM was developed in 1989 based on the "plug-compatible" concepts outlined in Kalnay et al. (1989). The GCM was subsequently improved in 1991 (Fox-Rabinovitz, et al. 1991, Helfand et al. 1991). The Relaxed Arakawa-Schubert cumulus convective parameterization and the re-evaporation of falling rain are based upon the works of Moorthi and Suarez (1992) and Sud and Molod (1988). The long-wave and short-wave radiation is parameterized following Chou and Suarez (1994). The planetary boundary layer and the upper level turbulence parameterizations are based on the level 2.5 closure model of Helfand and Labraga (1988) and Helfand et al. (1991). The orographic gravity wave drag parameterization follows Zhou et al. (1995). The model physics is updated with different frequencies ranging from every two dynamics time steps for turbulence and gravity wave drag, three dynamics time steps for moist processes (convection and large-scale precipitation) to one hour for short-wave and three hours for long-wave radiation. All model physics updates are prorated and applied at every time step.

The dynamical core of the GEOS GCM is described by Suarez and Takacs (1995) and its stretched-grid version by Fox-Rabinovitz et al. (1997). For the finite-difference approximation, the horizontal staggered Arakawa C grid (Mesinger and Arakawa 1976) and the vertical staggered Lorenz (1960) grid, are used. The equations of motion are approximated with the scheme developed by Sadourny (1975), Burridge and Haseler (1977), and Arakawa and Lamb (1981). Under some simplifying assumptions, the scheme provides conservation of energy and potential enstrophy. The continuity, thermodynamic and moisture equation approximations provide conservation of mass, potential temperature and moisture (Suarez and Takacs 1995).

For a uniform grid, the scheme is of the second-order except for the advection of vorticity by the rotational component of the flow, which is of the fourth-order. In the horizontal, the polar Fourier and local Shapiro (1970) filters, are used. In the vertical, there are 70 sigma-levels spaced as in the GEOS GCM (Takacs et al. 1994). The vertical differencing is done according to the Arakawa and Suarez (1983) conservation scheme. The time integration scheme employs the leap-frog scheme and a Robert-Asselin time filter (Robert 1966, Asselin 1972). It is combined with the economical explicit scheme (Brown and Campana 1978, Schuman 1971, and Fox-Rabinovitz 1974). Following Brown and Campana (1978), a three-time-level averaging operator is applied to the pressure gradient force to provide stricter control of gravity wave instability. It results in using larger time steps, and does not require any significant changes in the numerical scheme except for introducing a certain order in which the model equations are integrated.

The numerics of the GEOS model, with all its desirable conservation and other properties, remains unchanged when using stretched grids. Two basic horizontal filtering techniques, using a refined polar or high-latitude Fourier filter (Takacs et al. 1999) and a Shapiro filter, are applied in the model directly to stretched-grid fields. The filtering approach provides a workable monotonic global solution.

Since the early 90s, the GEOS GCM is routinely run with 2 x 2.5 degree horizontal resolution and 70 layers in the vertical covering the entire tropospheric and stratospheric domain between the surface and the 0.01 hPa level. It is also used for long-term simulations such as those of the AMIP (Atmospheric Model Inter-comparison Project). Recently, the version with 1 x 1 degree horizontal resolution and 48 layers in the vertical has been developed. It is used in this study for the 1993 SG-GCM experiment with finer 40 km regional resolution (see Section 5).

The GEOS GCM is used as a component within the GEOS DAS for producing the background first guess or 6 hour forecast fields. The Physical-space Statistical Analysis System (PSAS) is used for producing analyses within the GEOS DAS. It is based on the concept of minimizing the variance of analysis error. This minimization is achieved through finding an appropriate combination of observation and background fields (e.g. Cohn et al. 1998). The incremental analysis update (Bloom et al. 1996) is implemented to control initial imbalance problems. The GEOS DAS was developed and used for producing global reanalyses for climate and other applications. Its variable resolution version, the GEOS SG-DAS is used in this study in a special simulation mode for imitating a nested-grid framework, and for producing the verifying regional analyses.

3. The stretched grid generator and the experimental setup

A flexible, portable global stretched grid design employed in the study allows one to allocate the area of interest with uniform fine horizontal (latitude x longitude) resolution over any part of the globe such as the rectangle over the U.S. used for our experiments (Fig. 1). Outside the region, grid intervals increase, or stretch, with latitude and longitude as a geometric progression with the constant local stretching factor or ratio defined as follows:

$$r_j = dx_j / dx_{j-1} , \tag{1}$$

where dx_j and dx_{j-1} are adjacent grid intervals, and j is the horizontal index. The total global stretching factor is defined as

$$R = dx_{max} / dx_{min} , \tag{2}$$

where dx_{max} and dx_{min} are the maximal and minimal grid intervals on the sphere, relatively.

Note that if the area of interest includes the polar point or even the vicinity of the pole the stretched grid has to be rotated so that, for example, the polar point will be placed on the equator in the rotated coordinates.

In order to keep under control undesired computational problems arised from grid irregularity, some important properties of the stretched-grid design have to be imposed (Vichnevetsky 1987, Fox-Rabinovitz 1988, Fox-Rabinovitz et al. 1997). First, the stretching should be uniform, i.e. with r_j = constant for all j's. Second, as it was indicated in introduction, the stretching has to be "conservative" in the sense that the local stretching factors should not usually deviate from unity by more than about 5-10%. This allows one to have very fine mesoscale resolution over the area of interest (e.g. Cote et al. 1993, 1997, Fox-Rabinovitz et al. 1997) while keeping the resolution everywhere to be no worse than a few degrees of resolution of typical GCMs. A significant percentage of the total number of global grid points are then located within the area of interest. This reduces the amount of computations needed over the rest of the globe. Within a "conservative" stretching strategy, keeping the maximal grid intervals under control is needed for preserving the general integrity of global fields that is necessary for providing consistent interactions between global and regional scales throughout SG-GCM integrations.

As an option, the spherical stretched grid can be rotated so that the area of interest is located for example, about the equator in the rotated coordinates (e.g. Takacs et al. 1994). For the U.S. territory, such a rotation is not necessary but makes sense for the regions including the pole or located in a close proximity to the pole.

It is noteworthy that the "conservative" SG-parameters needed for the regional climate simulation mode could be quite relaxed for other modes of integration such as a short-term forecasting mode (Cote et al. 1993, 1998), and for a data assimilation mode.

The choice of stretched-grid parameters depends on a particular model design, configuration, requirements, and modes of integration. It also depends on a model's numerical scheme.

Let us describe now the special mode of integration introduced in this study. As mentioned above, the stretched grid approach has already been extensively tested with usual modes of integration such as the dynamical core experiments (Fox-Rabinovitz et al. 1997, 1999), the straightforward simulation mode for the full diabatic SG-GCM (Fox-Rabinovitz et al. 2000), and the data assimilation mode. For this study goals, the special unusual mode of integration has been introduced. Namely, the SG-DAS is run with withholding all the observational data over the area of interest. As the result, over the region of interest the SG-GCM is run with lateral boundary information provided from the SG-DAS analyses. It is noteworthy in this context that the term "boundary conditions" has been intentionally avoided here because there is no real lateral boundary for this kind of regional integration using a variable-resolution global model. his mode of integration imitates the nested-grid approach within which the inner model is driven by lateral boundary conditions obtained from reanalyses. Note that for the PIRCS (Takle et al. 1999) the NCEP reanalyses are used as lateral boundary conditions for the participating nested-grid models. In our case, our own SG-DAS analyses are used outside the region of interest and no computational buffer is needed due to monotonic noise free solution provided by SG-GCM. It is worth clarifying that no re-initialization over the area of interest is used for the described special integration mode.

This special mode of integration which will be referred to hereafter as the NG-simulation, is useful for inter-comparison purposes like those of the PIRCS, and for underlining the computational differences between the two approaches.

We proceed now with describing the experimental setup.

The stretched grid used in this study for 60 km regional resolution has the same number of grid points as the global uniform 2x2.5 degree grid but redistributed according to a SG-design (Fig. 1). The area of interest is the spherical rectangle over the U.S. with 60 km uniform resolution and the following coordinates: from 25N to 50N and from 125W to 75W. For the stretched grid, the local stretching factors (1) are ~7% and ~5% and the total global stretching factors (2) are ~9 and ~8 (that corresponds to the maximal grid intervals of ~4.5 and ~5.5 degrees), for latitudes and longitudes, relatively. The stretched grid has approximately 9 times less grid points than that of the global uniform 60 km resolution grid.

The stretched grid with finer 40 km regional resolution is obtained by redistributing the same number of grid points as in the global uniform 1 x 1 degree grid. The area of interest has the same coordinates as those of the 60 km regional resolution grid. The 40 km stretched grid also has an order of magnitude less grid points than that of the global uniform 40 km resolution grid.

The NCEP data analyses are used for surface boundary forcing, namely, the weekly analyses of SST, snow, and sea ice distributions, and the monthly analyses of soil moisture. The forcing with 2 and 1 degree resolutions is used for 60 km and 40 km SG-GCM experiments, correspondingly. Also, for the 40 km stretched grid , the land-sea differences are better resolved than for the 60 km stretched grid.

Orography is calculated directly on a stretched-grid by averaging, within a grid box, the Navy 1/6 x 1/6 degree surface elevation dataset available from the National Center for Atmospheric Research (NCAR). The grid box averaged orography is passed through a Lanczos(1966) filter in both dimensions which removes the smallest scales while inhibiting Gibbs phenomena (Takacs et al. 1994). The impact of orography filtering is discussed by Fox-Rabinovitz et al. (1999).

The SG-GCM experiments for 1988 and 1993 are started from initial conditions at 12Z May 15 and continued through July 15 for 1988 and July 31 for 1993. These initial conditions were obtained from the GEOS SG-GCM runs that started two week earlier, on May 1 of 1988 or 1993, to avoid the initial system spin-up effects.

Prognostic and time-averaged diagnostic fields like precipitation are stored every 6 hours. The prognostic variables (wind components, temperature, moisture and surface pressure) for the dynamical model state are updated and stored on the model dynamics stretched grid. The diabatic tendencies are updated at the appropriate physical/computational time-scales on their own physical (intermediate uniform) grid. Then they are interpolated, prorated per time step and applied at every time step to the model dynamics stretched grid. Therefore, the whole integration history resides effectively on the stretched grid.

Such an approach is justified by the assumption that model physics and dynamics can have different temporal and spatial resolution. This subject has been discussed by Lander and Hoskins (1997). For a spectral model, they advocate using coarser resolution for model physics than for model dynamics, and further conclude that similar considerations also apply to finite-difference and finite-element models.

At this stage of the SG-GCM development implementing model physics on an intermediate uniform resolution grid allows us to avoid some potential complications that may arise from calculating all model physics parameterizations on a stretched grid. It was verified that for such a combination of the SG-model dynamics and intermediate uniform grid model physics, the model physics captures ("sees") the finer scale patterns produced on the stretched grid.

The similar approach is employed for combining analysis and first guess fields within the SG-DAS. It is noteworthy that model and observational or analysis resolution have not to be necessarily the same. The effective observational resolution depends on the averaged distances between observation locations and, therefore, differ for different regions or subregions. It allows us to produce analyses on the intermediate uniform grid and then interpolate onto the model stretched grid. It allows us to use the existing statistical structures for the SG-DAS. Introducing the variable resolution anisotropic statistical structures will be done later.

A strict ultimate validation approach used in this study is comparing the simulated fields against data assimilation products or against observational gauge precipitation. Using the SG-DAS data assimilation products over the U.S.

with its high quality dense observational network, allows us to calculate the mean errors or biases and rms errors as the deviations of simulated fields from the corresponding verifying analyses.

4. Simulated prognostic fields

In this section, the time-averaged regional prognostic fields simulated by the SG-GCM for the 1988 and 1993 events with 60 km regional resolution, are compared against the corresponding time-averaged verifying analyses produced by the SG-DAS with the same regional resolution. The special mode of integration described in the previous section, the NG-simulation, is used for all the experiments presented in this and the next sections.

The time-averaged 500 hPa heights obtained by the NG-simulation for June 1988 and their bias or deviation from the SG-DAS verifying analyses, are presented in Fig.2. The strong ridge over the central part of the U.S. and two troughs on the east and west coasts, that comprise the pattern of the drought, are very well represented in the 500 hPa height field (Fig.2a) that is remarkably close to the verifying analyses, with only a few meter bias (Fig.2b).

Similar results are obtained for the NG-simulation for sea level pressure (SLP) shown in Fig.3a. The maximum bias for the field located over the central part of the U.S., is only 1 hPa whereas over the rest of the region the bias is even smaller than that, only a fraction of 1 hPa (Fig.3b). For the more meteorologically active flood period of July 1993, the bias is approximately twice larger but still small, within 2 hPa (Fig.3c).

For the same NG-simulation as shown in Fig.2, the monthly mean 500 hPa height rms errors or rms deviations from the SG-DAS verifying analyses, are shown in Fig.4a. The NG-simulation is performed with the data insertions every 6 hours, with the same frequency as for the SG-DAS used for producing the verifying analyses. The maximum rms error is small, only 15 m, and is located in the middle of the area of interest. Over the rest of the area, the rms errors are even smaller, mostly in single digits.

For different nested grid models, boundary conditions are usually updated every 6, 12, or 24 hours. For the NG-simulations employing the SG-approach, no boundary conditions are needed but the boundary information outside the area of interest is affected by the frequency of data insertion or updates. The NG-simulations were performed with all three of the above frequencies. Their rms errors are presented in Fig.4. Using the 12 hour frequency does not result in any increase or pattern change of the rms errors (Fig.4b) compared to those of the 6 hour frequency (Fig.4a). Boundary information for the NG-simulations is about the same because radiosonde data are observed only every 12 hours. However, the rms errors for the 24 hour frequency (Fig.4c) are slightly, only a few meters, larger over the whole region, especially over its southwestern part where the maximum of 22 m is located. This maximum is a result of inflow information from the South Pacific that is poorly covered with observational data. Therefore, although the 24 hour frequency updates produce quite limited rms errors the 6 or 12 hour frequency updates produce slightly better results that is consistent with the experience obtained with nested grid models.

All of the above biases and rms errors are so small that they do not exceed the typical observational errors for the corresponding fields. Other prognostic variables show the similar behavior.

It is noteworthy that the biases and rms errors for the NG-simulations are smaller than those presented by Takle et al. (1999) for the U.S. drought of 1988 for the nested grid models of the PIRCS.

5. Simulated precipitation

The 1988 and 1993 U.S. anomalous regional climate events are chosen by the PIRCS to investigate how different regional climate models simulate the anomalous summer precipitation cases, like a drought and a flood, for intra-seasonal time scales. In the section, the NG-simulations presented in the previous section are further analyzed in terms of their ability to produce regional precipitation patterns. Also, the impact of finer 40 km regional resolution is considered in terms of reproducing subregional precipitation patterns. Both the SG-DAS precipitation and the NCEP gauge precipitation over the U.S. are used for validation of the NG-simulations.

The monthly mean gauge precipitation data for June 1988, the drought case, is shown in Fig.5c. The extensive drought in the central U.S., mostly in the northern and central parts of the Mississippi River basin, is characterized by the precipitation rates that are less or about 1 mm/day. For the NG-simulation with 60 km regional resolution (Fig.5a),the drought area is quite appropriately located and the precipitation rates for the area are less than 2 mm/day. Another important feature of the precipitation pattern, the intensive (up to 4 mm/day) precipitation in southern Louisiana around the Mississippi River delta (Fig.5c) is well represented in the NG-simulation (Fig.5a). Precipitation simulated over the western Texas (Fig.5a) is only partly supported by gauge data (Fig.5c). The intensive, up to 5mm/day, precipitation over Florida (Fig.5c) is overestimated by the NG-simulation (Fig.5a). Precipitation over the northwestern New Mexico, with the maximum of 3 mm/day (Fig.5c), is reflected although overestimated in the NG-simulation (Fig.5a). A subregional maximum of 2 mm/day over Oregon and Washington (Fig.5c) is present in the NG-simulation (Fig.5a) as well. All that shows that the NG-simulation pattern (Fig.5a) is close to that of gauge data (Fig.5c).

The similarity of the patterns is reflected in the bias or deviation from the SG-DAS precipitation shown in Fig.5b. The bias is less than or about 1 mm/day for almost all of the aforementioned areas as well as over the Rockies and the entire western part of the U.S. It is larger, about 2 mm/day, for the areas surrounding the drought area.

The rms differences between precipitation produced by the NG-simulations with different frequency (6, 12, or 24 hour) data insertions or updates and that of produced by the SG-DAS, are shown in Fig.6. The rms differences are quite small, about 1 mm/day, over the drought area and the entire western part of the U.S. as well as over the east coast and surrounding areas. The rms differences are basically close for all of the above frequency updates that is consistent with the results for the 500 hPa heights shown in Fig.4.

The results of another NG-simulation of the anomalous regional climate event, the intensive U.S. summer flood of 1993, produced with 60 km regional resolution, are presented in Fig.7a. The NCEP gauge precipitation data used for validation of the NG-simulation are shown in Fig.7b. It is worth pointing out that gauge data only over the U.S. are used for producing the NCEP data (Fig.7b) whereas precipitation over the entire area of interest (including the strong precipitation over the northern part of Mexico) is present in Fig.7a.

The NG-simulation (Fig.7a) shows a profound similarity to verifying precipitation data (Fig.7b), in terms of the precisely correct location and intensity of the flood. The maximum of 12 mm/day (Fig.7a) coincides with that of gauge data (Fig.7b). The precipitation pattern over the rest of the region, especially over the northern part of the U.S. (Fig.7a), with the maximum over North Dakota, is very close to that of verifying precipitation data (Fig.7b). Precipitation in northwestern Mexico is appropriately located in the NG-simulation (Fig.7a) although overestimated compared to that of the NCEP (Xie-Arkin) blended satellite and gauge precipitation data (not shown). Over the east coast area including Florida, the NG-simulation (Fig.7a) precipitation pattern is quite close to that of gauge precipitation data (Fig.7b). The NG-simulation (Fig.7a) produced intensive precipitation over Wyoming and Montana as well as around the Seattle-Vancouver area that are not present in Fig.7b. However, Bosilovich and Sun (1999) produced less smoothed gauge precipitation data for July 1993 (see Fig.5 of their paper) with quite intensive precipitation for the aforementioned areas.

The NG-simulation (Fig.7a and Fig.8b) failed to reproduce intensive precipitation in the southeastern part of the U.S., especially over the Mississippi River delta in southern Louisiana, Mississippi and Alabama (Fig.7b and Fig.8c). This intensive subregional precipitation is well recovered in the NG-simulation calculated with finer 40 km regional resolution (Fig.8a). This subregional precipitation (Fig.8a) is even closer to less smoothed gauge precipitation of Bosilovich and Sun (1999) (see Fig.5 of their paper).

The results presented in sections 4 and 5 show the potential of the SG-GCM in simulating anomalous regional climate events.

6. Conclusions

1. The SG-GCM is used in the study in a special regional climate integration mode (the NG-simulation) that is consistent with the nested grid framework employed for the PIRCS. The special integration mode is successfully used for simulation of two anomalous U.S. summer climate events chosen for the PIRCS, the drought of 1988 and the flood of 1993.

2. The monthly mean patterns and biases and rms errors for prognostic fields of the NG-simulations calculated with 60 km regional resolution, show profound similarity, within the observation error ranges, to the verifying analyses produced with the SG-DAS with the same regional resolution.

3. Using different (6, 12, or 24 hour) frequencies of data insertion for updating boundary information for the 1988 NG-simulation (with no boundary conditions or computational buffer needed within the SG-approach providing a noise-free monotonic solution) has not resulted in any significant growth of biases and rms errors for prognostic variables.

4. The monthly mean precipitation patterns for the NG-simulation appeared to be remarkably close to those of verifying gauge precipitation data. The intensive precipitation for the 1993 summer flood area is very well simulated

in terms of the precisely correct location and the intensity of the event.

5. The precipitation rms errors for the 1988 NG-simulation do not significantly grow for different frequency of data insertion or updates (every 6, 12, or 24 hours) that is consistent with the aforementioned results for prognostic variables.

6. The NG-simulations produced with finer 40 km regional resolution resulted in recovering the subregional intensive precipitation over southern Louisiana, Mississippi, and Alabama where it was underestimated in the NG-simulations with 60 km resolution.

7. The analysis of performed experiments shows the potential of the SG-GCM (and the SG-approach in general) for successful simulation of anomalous regional climate events.

Acknowledgments. The author would like to thank Mr. R. C. Govindaraju for programming support, and Ms. Q. Philpot for typing the manuscript. The study has been supported by NASA Grant 578-41-11-20 and the DOE Grant DE-FG02-98ER62618. The authors would like to thank Dr. Kenneth Bergman, the NASA Program Manager, and Dr. Jerry Elwood, the DOE Program Manager, for their support of the study.

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Figure captions

Fig.1 An example of a stretched grid with the area of interest with enhanced regional resolution over the U.S.

Fig.2 Monthly (June 1988) mean 500 hPa heights: (a) for the regional simulation mode imitating the nested grid framework (NG-simulation), with 60 km regional resolution; (b) bias or the difference between (a) and the verifying analyses obtained from the SG-DAS with 60 km regional resolution. The contour intervals are 50 m for (a), and 1 m for (b).

Fig.3 (a) and (b) are as in Fig.2 but for sea level pressure (SLP); and (c) as (b) but for July 1993. The contour intervals are 2 hPa for (a), 0.2 hPa for (b), and 0.5 hPa for (c).

Fig.4 Monthly (June 1988) mean 500 hPa height rms differences between the NG-simulations and the SG-DAS verifying analyses different frequencies of data insertions/updates: (a) every 6 hours; (b) every 12 hours; and (c) every 24 hours. The contour interval is 1 m.

Fig.5 (a) and (b) are as in Fig.2 but for precipitation; and (c) NCEP gauge precipitation data. The contour intervals are 2 mm/day for (a) and (c), and 1 mm/day for (b).

Fig.6 As in Fig.4 but for precipitation. The contour interval is 1 mm/day.

Fig.7 Monthly (July 1993) mean precipitation for: (a) the NG-simulation; (b) NCEP gauge precipitation data. The contour intervals are 2 mm/day for (a) and (b).

Fig.8 Monthly (July 1993) mean precipitation for the southeastern part of the U.S. for: (a) the NG-simulation calculated with 40 km regional resolution; (b) same as (a) but for 60 km resolution;and (c) NCEP gauge precipitation data. (Note that (b) and (c) show the subregional fields presented for the entire U.S. region in Fig.7a and b, relatively). The contour interval is 1 mm/day.