Dynamical Downscaling: Assessment of Value Retained and Added Using the Regional Atmospheric Modeling System (RAMS)

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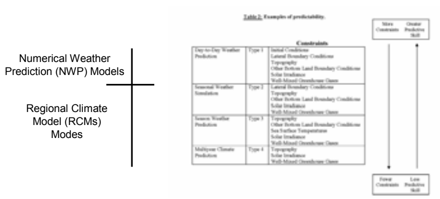
Introduction

The term "downscaling" refers to the use of either fine-scale spatial-scale atmospheric models (dynamical downscaling) or statistical relationships (statistical downscaling) in order to achieve detailed regional and local atmospheric data. The starting point for downscaling is typically a larger-scale atmosphere or couple ocean-atmosphere model run globally (GCM). The downscaled high resolution data can then be inserted into other types of numerical tools such as hydrological, agricultural, and ecological models. Here we focus on dynamical downscaling with a regional climate model (RCM). By RCM we mean a limited area (weather prediction) model (LAM) run for an integration time greater than approximately two weeks, so that the sensitivity to initial conditions is lost. By examining a sample case with the Regional Atmospheric Modeling System (RAMS), we present evidence of when downscaling may be a valid tool to enhance spatial resolution and when it is not.



Here the value retained and value added by dynamical downscaling is quantitatively evaluated by considering the spectral behavior of the RAMS model solution in relation to its domain size and grid spacing. By "value retained" we mean how well the RCM maintains fidelity with the large-scale behavior of the global model forcing data. By "value added" we mean how much additional information the RCM can provide beyond the highest resolved wavelength of the global model. We assume "perfect" bottom and lateral boundary conditions, as defined by observed SSTs and atmospheric reanalyses (Type 2 simulations). We extend previous work with RAMS to show that, absent a means of updating the interior of the domain, the RCM cannot retain value of the large scale. We then show the value added, or RCM skill, is dependent on how the large scale is represented, how the surface boundary is specified, and the model physics.

Methodology of Basic Experiments and Analysis

RAMS simulations were executed for the month of May 1993 for the grid domains in Fig. 1 at 200 km, 100 km, and 50 km grid spacing for a total of six basic experiments. Data were saved every 12h. For each analysis time, the corresponding reanalysis data were vertically and horizontally interpolated to the RAMS grid. The variables considered for analysis are the integrated kinetic energy and integrated moisture flux convergence. The KE is more sensitive to the large scale forcing and the MFC is more sensitive to the surface forcing.

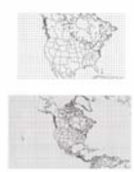


Figure 1: RAMS domains for model sensitivity experiments (Δx = 200km)

RAMS Model Conditions for Basic Experiments

•Lateral boundaries updated every 6h by NCEP Reanalysis using a Davies (1976) nudging technique for three boundary points.

•Fixed surface boundary conditions: topography, sea surface temperature, soil type, soil moisture, and vegetation.

•Simplest and most computationally expedient parameterizations. For rainfall, rely exclusively on Kuo convection scheme.

Data from the basic experiments (mod) and regridded reanalysis (obs) were spectrally decomposed using the method of Errico (1985). This analysis generates a one-dimensional spectrum for each analysis time. Spectra were then averaged over the over the last fifteen days of model simulation when RAMS is operating in a RCM mode.

Important Definitions for Spectral Analysis:

Fractional change in spectral power: To compare spectral power per wavenumber between the reanalysis and the RCM, the fractional change in spectral power is computed as:

$$\Delta S(k)_{frac} = S(k)_{mod}/S(k)_{obs} - 1 \quad \text{Where } S(k) \text{ is the time averaged spectrum.}$$

Approximate Nyquist wavenumber and wavelength of reanalysis (wavenumber of $2\Delta x$ waves)

$$k^*_{Nyquist} = 1.13 \times 10^{-5}\ \text{m}^{-1} \qquad \lambda_{Nyquist} = 550\ \text{km}$$

Wavenumber and wavelength of physically resolved waves in the reanalysis (wavenumber of $4\Delta x$ waves)

$$k^*_{max} = 5.65 \times 10^{-6}\ \text{m}^{-1} \qquad \lambda_{max} = 1100\ \text{km}$$

k^*_{max} defines the boundary between "large" ($k<k^*_{max}$) and "small" ($k>k^*_{max}$) scales in the spectral analyses.

Basic Experiments: Investigation of Value Retained

An illustration of loss of large-scale variability with simulated 500-mb height

We select a sample model-simulated day with a highly amplified 500-mb height field. This particular day is 12 days from model initialization, and it is generally illustrative of what RAMS produces in a Type 2 downscaling mode. Significant synoptic features apparent in the reanalysis are not present in the model simulations. For example, the ridge in the central U.S. is too far south and west, and the cutoff lows off the California coast and in the central U.S. are not as strong or appear as open waves. The height field degrades with increased domain size.

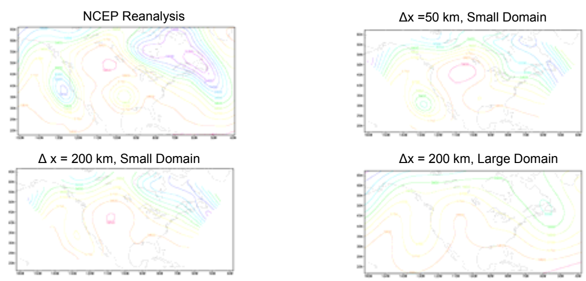


Figure 2: Observed 500-mb height on 0Z UTC 12 May 1993 for constraints indicated

Plots of the fractional change in spectral power for the last 15 days of simulation

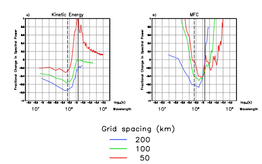


Figure 3: Fractional change in spectral power versus $\log_{10}(k)$ and wavelength, small domain experiments for a) KE and b) MFC. The dashed line indicates k^*_{max} and the solid black line $k^*_{Nyquist}$. k in units of m^{-1}. Wavelength in units of m.

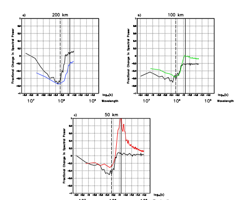


Figure 4: Fractional change in spectral power versus $\log_{10}(k)$ for KE, small and large domain experiments a) Δx = 200 km, b) Δx = 100 km, and c) Δx = 50 km. Small domain experiments color coded as in Fig. 4 and large domain experiments shown as corresponding solid black curve. k^*_{max} and $k^*_{Nyquist}$ same as in Fig.3. k in units of m^{-1}. Wavelength in units of m.

Behavior of fractional change in spectral power:

- Large scale: The RCM underestimates the spectral power of KE and does not retain value of the reanalysis. Greatest underestimation appears to be at k^*_{max}.
- Small scale: The model adds value to KE at 50 km grid spacing, but not at 100 km or 200 km grid spacing
- The problem with underestimation of the large scale variability tends to worsen with increases in domain size and grid spacing.

Time Evolution of Domain-Averaged Model Simulated to Reanalysis KE

Regardless of grid spacing or grid size, the ratio of model simulated to regridded reanalysis kinetic energy in all of the basic experiments decreases approximately logarithmically in time. As the grid spacing for the small domain increases, the loss of kinetic energy worsens more so than for the larger domain. This is also true for the large domain analyzed over the small domain with equivalent grids. Considering the same area in all the simulations, the loss in kinetic energy also worsens with increased domain size. For the 200 km grid spacing large domain, the model underestimates the observed kinetic energy by nearly 50% after thirty days of simulation.

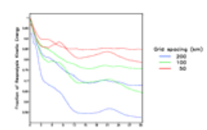


Figure 5: Time evolution of the fraction of model simulated to reanalysis regridded domain average total kinetic energy for the six basic experiments on equivalent grids. The small domain is indicated by a solid curve and the large domain is indicated by a dashed curve.

Follow-on Experiments: Investigation of Value Added

Four additional follow-on experiments were performed to investigate the effect of internal nudging, a larger grid, a change in the convective parameterization (to the Kain-Fritsch scheme), and a homogeneous surface boundary. These were performed with the grid of the 50 km small domain because that maintained the best fidelity with the reanalysis on the small scale. These additional simulations are designed to assess the value added by RAMS for small scales. In these cases, the fractional spectral power is computed as the ratio of the modified simulation compared to the basic experiment. Spectral ratio results are shown for three of the four experiments.

Follow-on #1: Internal Nudging

Improves model representation of kinetic energy on the large scale, but decreased variability on the small scale. MFC variability decreased for all k due to weaker vertical motion.

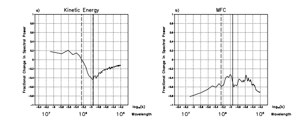


Figure 6: Average fractional change in spectral power vs. $\log_{10}(k)$ and wavelength for a) KE and b) MFC for Follow-on 1. The dashed line indicates k^*_{max} and the solid black line $k^*_{Nyquist}$. Wavelength in units of m.

Follow-on #2: Grid Enlargement

Increasing the domain size reduces variability of KE for all k. However, MFC variability is increased at small scales, likely due to increased influence of the surface boundary.

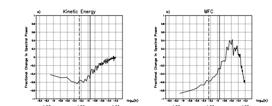


Figure 7: Same as Fig. 6 for Follow-on 2.

Follow-on #3: Different Convection Scheme

No change in the KE variability at large scales, but an increase in KE variability at the small scales. Variability in MFC is larger for all k, particularly at small scales. The Kain-Fritsch scheme appears to be more sensitive to the surface boundary.

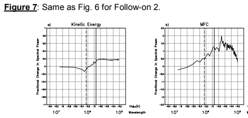


Figure 8: Same as Fig. 6 for Follow-on 3.

Precipitation solutions for the last 15 days of model simulation show a large sensitivity to user-defined parameters in the RCM. In general, the weaker the influence of large-scale forcing, the greater the domain-averaged rainfall and greater influence of the topography on rainfall. Presumably the same effect would exist for variation in other surface properties, like soil moisture, vegetation, and snow cover. Though internal nudging decreases the precipitation, it increases the fidelity to observations.

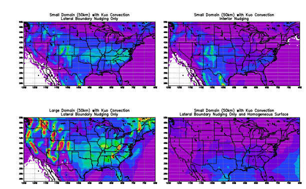


Figure 9: RAMS simulated convective precipitation with Kuo scheme for model constraints indicated. Period considered is the last 15 days of simulation. Precipitation in mm.

Conclusions

1. Absent some method of large-scale closure (i.e., interior or spectral nudging), RAMS as a RCM will have greater error at larger scales as both horizontal grid spacing and domain size increase. The error is due to the failure of the RCM to correctly retain value of the large scale, which is particularly acute at the limit of physically resolved waves in the GCM or reanalysis.
2. RAMS does add value for the small scale, especially if there is sufficient surface boundary forcing, and that forcing can be resolved.
3. The cause of the loss of large-scale kinetic energy with time, absent interior nudging, is likely due to the fact that some or all of the one-dimensional column parameterizations are insufficiently accurate and are thus unable to retain or generate accurate simulations of the large-scale atmospheric features.
4. The change in trend at k^*_{max} seems to be a robust feature of the analysis. If this dependence occurs irrespective of the resolution of the GCM, it would be possible to determine a priori which wavelengths the RCM would tend degrade, absent some interior nudging technique.
5. These experiments should be repeated with other RCMs to verify whether these behaviors are universal to all RCMs. Preliminary work on this has indicated our results are independent of the RCM.

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