Chapter III – The Added Value of Regional Climate Model Simulations

Types of downscaling simulations

This section focuses on downscaling using three-dimensional models based on fundamental conservation laws, i.e., numerical models with a similar basis as GCMs. A later section of the chapter discusses an alternative approach, statistical downscaling. There are three primary approaches to numerical downscaling: limited-area models (Giorgi and Mearns, 1991; McGregor, 1997; Giorgi and Mearns, 1999; Wang *et al*., 2004), stretched grid models (e.g., Deque *et al*.,1995; Fox-Rabinovitz *et al*., 2001, 2006) and uniformly high-resolution atmospheric GCMs (AGCMs) (e.g., Brankovic and Gregory, 2001; May and Roeckner, 2001; Duffy *et al*., 2003; Coppola and Giorgi, 2005). The last approach is sometimes called "time-slice" climate simulation because the AGCM simulates a portion of the period simulated by the parent, coarser resolution GCM that supplies boundary conditions to it. The limited-area models, also known as regional climate models (RCMs), have the most widespread use. All three approaches use interactive land models, but sea-surface temperatures and sea ice are generally specified from observations or an atmosphere-ocean GCM. All three approaches are also used for purposes beyond downscaling global simulations, most especially to study climatic processes and interactions on scales too fine for typical GCM resolutions.

RCMs, as limited-area models, cover only a portion of the planet, typical a continental domain or smaller. They require lateral boundary conditions from observations, such as atmospheric analyses (e.g., Kanamitsu *et al*. 2002, Uppala *et al*. 2005), or a global simulation. There has been limited two-way coupling wherein an RCM to supplies part of its output back to the parent GCM (Lorenz and Jacob, 2005). Simulations with observation-based boundary conditions are used not only for studying fine scale climatic behavior, but also to help segregate GCM error from error intrinsic to the RCM when performing climate-change simulations (Pan et al., 2001). RCMs may also use grids nested inside a coarser RCM simulation to achieve higher resolution in subregions (e.g. Liang *et al*., 2001; Hay *et al*., 2006). Stretched-grid models, like the high-resolution AGCMs, simulate the globe, but with spatial resolution varying horizontally. Highest resolution may focus on one (e.g. Deque and Piedelievre, 1995; Hope *et al*., 2004) or a few regions (e.g., Fox-Rabinovitz *et al*., 2002). In some sense, high-resolution AGCMs are a limiting case of stretched-grid simulations where the grid is uniformly high everywhere.

Highest spatial resolutions are most often several tens of kilometers, though some (e.g., Grell *et al*., 2000a,b; Hay *et al*., 2006) have simulated climate with resolutions as small as a few kilometers using multiply nested grids. Duffy *et al*. (2003) have performed multiple AGCM time-slice computations using the same model to simulate resolutions from 310 km down to 55 km. Such approaches expose changes in climate with resolution. Higher resolution generally yields improved climate, especially for fields with high spatial variability, such as precipitation. For example, some studies show that higher resolution does not have a statistically significant advantage in simulating large-scale circulation patterns but it does yield better monsoon precipitation forecasts and interannual variability (Mo *et al*., 2005) and precipitation intensity (Roads *et al*., 2003).

However, improvement is not guaranteed: Hay *et al*. (2006) find deteriorating timing and intensity of simulated precipitation versus observations in their inner, high-resolution nests, even though the inner nest improves resolution of topography. Extratropical storm tracks in a time-slice AGCM may shift poleward relative to the parent, coarser GCM (Stratton, 1999; Roeckner *et al*., 2006) or lower resolution versions of the same AGCM (Brankovic and Gregory, 2001), thus yielding an altered climate with the same sea-surface temperature distribution as the parent model.

Spatial resolution affects the length of simulation periods because higher resolution requires shorter time steps for numerical stability and accuracy. Required time steps scale with the inverse of resolution and can be one or two orders of magnitude smaller than AOGCM time steps. Since increases in resolution are most often applied to both horizontal directions, this means that computation demand varies inversely with the cube of resolution. Although several RCM simulations have lasted 20 to 30 years (Christensen *et al*., 2002; Leung *et al*., 2004; Plummer *et al*., 2006) and even as long as 140 years (McGregor, 1999) with no serious drift away from reality, stretched-grid, time-slice AGCM and RCM simulations typically last from months to a few years. Vertical resolution usually does not change with horizontal resolution, though Lindzen and Fox-

Rabinovitz (1989) and Fox-Rabinovitz and Lindzen (1993) have expressed concerns about the adequacy of vertical resolution relative to horizontal resolution in climate models.

Higher resolution in RCMs and stretched-grid models must also satisfy numerical constraints. Stretched-grid models whose ratio of coarsest to finest resolution exceeds a factor of roughly three are likely to produce inaccurate simulation due to truncation error (Qian *et al*., 1999). Similarly, RCMs will suffer from incompletely simulated energy spectra and thus loss of accuracy if their resolution is roughly 12 times or more finer than the resolution of the source of lateral boundary conditions, which may be coarser RCM grids (Denis *et al*., 2002, 2003; Laprise, 2003; Antic *et al*., 2004, 2006; Dimitrijevic and Laprise 2005). In addition, these same studies indicate that lateral boundary conditions should be updated more frequently than twice per day.

Additional factors also govern ingestion of lateral boundary conditions (LBCs) by RCMs. LBCs are most often ingested in RCMs by damping of the model's state toward the LBC fields in a buffer zone surrounding the domain of interest (Davies, 1976; Davies and Turner, 1977). If the buffer zone is only a few grid points wide, the interior region may suffer phase errors in simulating synoptic-scale waves (storm systems), with resulting error in the overall regional simulation (Giorgi et *al*.,1993). Spurious reflections may also occur in at boundary regions (e.g., Miquez-Macho et *al*., 2005). RCM boundaries should be where the driving data are of optimum accuracy (Liang et *al*., 2001), but placing the buffer zone in a region of rapidly varying topography can induce surface pressure errors due to mismatch between the smooth topography implicit in the coarse resolution driving data and the varying topography resolved by the model (Hong and Juang 1998). Domain size may also influence RCM results. If a domain is too large, the model's interior flow may drift from the large-scale flow of the driving data set (Jones et *al*., 1995). However, too small a domain overly constrains interior dynamics, preventing the model from generating appropriate response to interior mesoscale-circulation and surface conditions (Seth and Giorgi, 1998). RCMs appear to perform well for domains roughly the size of the contiguous United States. **Figure III.A** shows that the daily, root-mean-square difference (RMSD) between simulated and observed (reanalysis) 500 hPa heights is generally within observational noise levels (roughly 20 m).

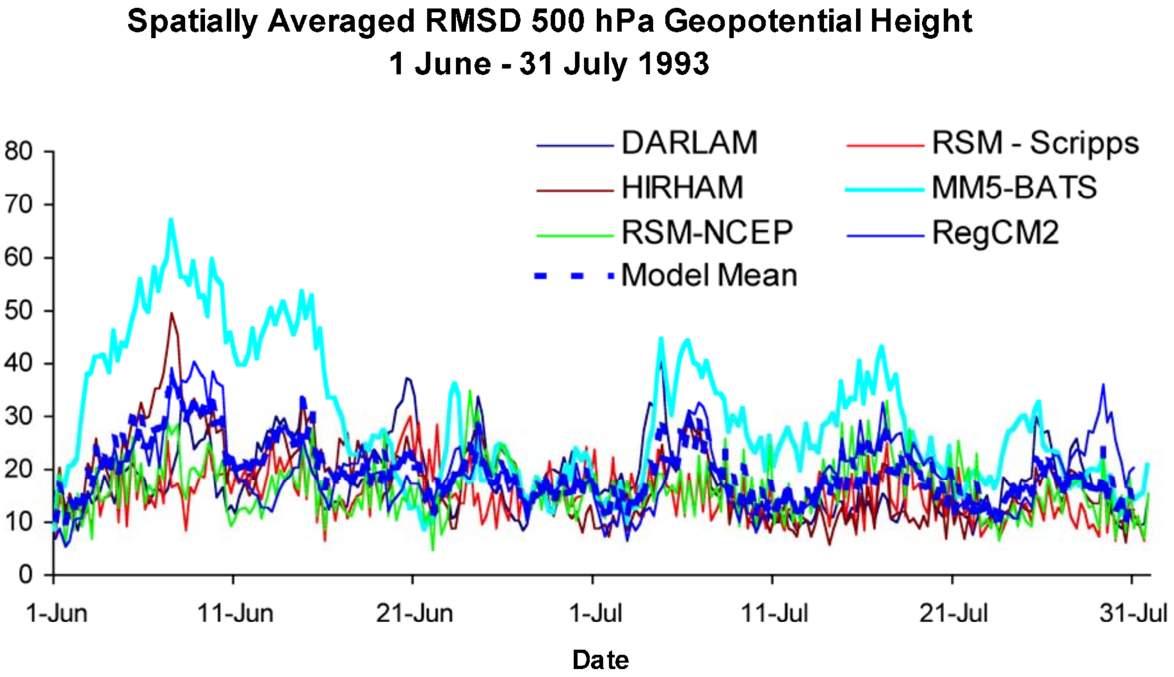

Figure III. A. Daily root-mean-square differences (RMSD) in 500 hPa height between observations (reanalysis) and 6 models participating in the PIRCS 1b experiment (Anderson *et al*., 2003). RMSD values averaged over the simulation domain inside the boundary-forcing zone. Also shown is the mean curve for the 6 models. (y-axis scale: meters).

Because simulations from the downscaling models may be analyzed for periods as short as a month, model spin-up is important (e.g., Giorgi and Bi, 2000). During spin-up the model evolves to conditions representative of its own climatology, which may differ from the sources of initial conditions. The atmosphere spins up in a matter of days, so the key factor is spin-up of soil moisture and temperature, which evolve more slowly. Equally important, data for initial conditions is often lacking or has low spatial resolution, so that initial conditions may be only a poor approximation to the model's climatology. Spin-up is especially relevant for downscaling because these models are presumably resolving finer surface features than coarser models, with the expectation that the downscaling models are providing added value through proper representation of these surface features. Deep soil temperature and moisture, at depths of 1–2 meters, may require several years of spin up. However, these deep layers generally interact weakly with the rest of the model, so shorter spin-up times are used. For multi-year simulations, 3–4 years appears to be a minimal requirement (Christensen, 1999; Roads *et al*., 1999). This ensures that the upper meter of soil has a climatology in further simulation that is consistent with the evolving atmosphere.

Many downscaling simulations, especially with RCMs, are for periods much shorter than two years. Such simulations likely will not use multi-year spin up. Rather, these studies may focus on more rapidly evolving atmospheric behavior that is governed by lateral boundary conditions, including extreme periods like drought (Takle *et al*.,1999) or flood (Giorgi *et al*., 1996; Liang *et al*., 2001; Anderson *et al*., 2003). Thus, they assume that the interaction with the surface, while not negligible, is not strong enough to skew the atmospheric behavior studied. Alternatively, relatively short regional simulations may specify, for sensitivity study, substantial changes in surface evaporation (e.g., Paegle et *al*., 1996), soil moisture (e.g., Xue et *al*., 2001) or horizontal moisture flux at lateral boundaries (e.g., Qian *et al*., 2004).

Even with higher resolution than standard GCMs, models simulating regional climate still need parameterizations for subgrid-scale processes, most notably boundary-layer dynamics, surface-atmosphere coupling, radiative transfer and cloud microphysics. . Most regional simulations also require a convection parameterization, though a few have used sufficiently fine grid-spacing, a few kilometers, to allow acceptable simulation without one (e.g., Grell et al., 2000). Often, these parameterizations are the same or nearly the same as used in GCMs. However, all parameterizations make assumptions that they are representing the statistics of subgrid processes, and so implicitly or explicitly they require that the grid box's area in the real world would have sufficient samples to justify the stochastic modeling. For some parameterizations, such as convection, this assumption becomes doubtful when grid boxes become only a few kilometers in size (Emanuel 1994). In addition, models simulating regional climate may include circulation characteristics, such as rapid mesoscale circulations (jets) whose interaction with subgrid processes like convection and cloud cover differs from the larger scale circulations resolved by typical GCMs. This factor is part of a larger issue, that parameterizations may have regime dependence, performing better for some conditions than others. For example, the Grell (1993) convection scheme is responsive to large-scale tropospheric forcing, whereas the Kain and Fritsch (1993) scheme is heavily influenced by boundary-layer forcing. As a result, the Grell scheme simulates better the propagation of precipitation over the U.S. Great Plains that is controlled by the large-scale tropospheric forcing, while the Kain–Fritsch scheme simulates better late afternoon convection peaks in the southeastern U.S. that are governed by boundary-layer processes (Liang et *al*., 2004). As a consequence, parameterizations for regional simulation may differ from their GCM counterparts, especially for convection and cloud microphysics. As noted earlier, the regional simulation in some cases may have resolution of only a few kilometers and the convection parameterization may be discarded (Grell *et al*., 2000). A variety of parameterizations exist for each of these phenomena, with multiple choices often available in a single model (e.g., Grell *et al*., 1994; Skamarock *et al*., 2005).

The chief reason for performing regional simulation, whether by an RCM, a stretched-grid model or a time-slice AGCM, is to resolve behavior considered important for a region's climate that a global model does not resolve. Thus, regional simulation should have clearly defined regional-scale (mesoscale) phenomena targeted for simulation. These include, for example, tropical storms (e.g., Oouchi *et al.*, 2006), effects of mountains (e.g., Leung and Wigmosta, 1999; Grell *et al*., 2000; Zhu and Liang, 2007), jet circulations (e.g., Takle *et al*., 1999; Anderson *et al*., 2001; Anderson *et al*., 2003; Byerle and Paegle, 2003; Pan *et al.*, 2004) and regional ocean-land interaction (e.g., Kim *et al*., 2005; Diffenbaugh *et al*. 2004). The most immediate value, then, of regional simulation is to explore how such phenomena operate in the climate system, which becomes a justification for the expense of performing regional simulation. Phenomena and computational costs together influence the design of regional simulations. Simulation periods and resolution are balances between sufficient length and number of simulations for climate statistics versus computational cost. For RCMs and stretched-grid models, the sizes of regions targeted for high-resolution simulation are determined in part by where the phenomenon occurs.

In the context of downscaling, regional simulation offers the potential to include phenomena affecting regional climate change that are not explicitly resolved in the global simulation. When given boundary conditions corresponding to future climate, regional simulation can then indicate how these phenomena contribute to climate change. Results, of course, are dependent on the quality of the source of the boundary conditions (Pan *et al*., 2001; de Elía *et al*., 2002), though use of multiple sources of future climate may lessen this vulnerability and offer opportunity for probabilistic estimates of regional climate change (Raisanen and Palmer, 2001; Giorgi and Mearns, 2003; Tebaldi et *al*., 2005). Results also depend on the physical parameterizations used in the simulation (Yang and Arritt, 200; Vidale *et al*., 2003; Déqué *et al*., 2005; Liang et *al*., 2006). Advances in computing power suggest that typical GCMs will eventually operate at resolutions of most current regional simulations (a few tens of kilometers), so that understanding and modeling improvements gained for regional simulation can promote appropriate adaptation of GCMs to higher resolution. For example, interaction between mesoscale jets and convection appears to require parameterized representation of convective downdrafts and their influence on the jets (Anderson *et al*., 2007), behavior not required for resolutions that do not resolve mesoscale circulations.

Because of the variety of numerical techniques and parameterizations employed in regional simulation, many models and versions of models exist. Side-by-side comparison (e.g., Takle *et al*., 1999; Anderson *et al*., 2003; Fu *et al*., 2005; Frei *et al*., 2006; Rinke *et al*., 2006) generally shows no single model appearing as best versus observations, with different models showing superior performance depending on the field examined. Indeed, the best results for downscaling climate simulations and estimating climate-change uncertainty may come from assessing an ensemble of simulations (Giorgi and Bi, 2000; Yang and Arritt, 2002; Vidale *et al*., 2003; Déqué *et al*., 2005). Such an ensemble may capture much of the uncertainty in climate simulation, offering an opportunity for physically based analysis of the climate changes and also the uncertainty of the changes. Several regional models have performed simulations of climate change for parts of North America, but at present, there have been no regional projections using an ensemble of regional models simulating the same time periods with the same boundary conditions. Such systematic evaluation has occurred in Europe [PRUDENCE (Christensen *et al*., 2002) and ENSEMBLES (Hewitt and Griggs 2007) projects] and is starting in North America with the North American Regional Climate Change Assessment Program (NARCCAP 2007).

Empirical downscaling

Empirical, or statistical, downscaling is an alternative approach to obtaining regional-scale climate information (Kettenberg *et al*.,1996; Hewitson and Crane, 1996; Giorgi *et al*., 2001; Wilby *et al*., 2004, and references therein). It uses statistical relationships to link resolved behavior in GCMs with climate in a targeted area. The size of the targeted area can be as small as a single point. So long as significant statistical relationships occur, empirical downscaling can yield regional information for any desired variable, such as precipitation and temperature, as well as variables not typically simulated in climate models, such as zooplankton populations (Heyen *et al*.,1998) and initiation of flowering (Maak and von Storch, 1997). The approach encompasses a range of statistical techniques from simple linear regression (e.g., Wilby *et al*., 2000) to more complex applications, such as those based on weather generators (Wilks and Wilby, 1999), canonical correlation analysis (e.g., von Storch *et al*.,1993) or artificial neural networks (e.g., Crane and Hewitson, 1998). Empirical downscaling can be very inexpensive compared to numerical simulation when applied to just a few locations or using simple techniques. This together with the flexibility in targeted variables has led to a wide variety of applications for assessing impacts of climate change.

There has been some side-by-side comparison of methods (Wilby and Wigley, 1997; Wilby *et al*., 1998; Zorita and von Storch 1999; Widman *et al*., 2003). These studies have tended to show fairly good performance of relatively simple versus more complex techniques and to highlight the importance of including moisture as well as circulation variables when assessing climate change. There also has been comparison of statistical downscaling and regional climate simulation (Kidson and Thompson, 1998; Mearns *et al*.,1999; Wilby *et al*., 2000; Hellstrom *et al*., 2001; Wood *et al*., 2004; Haylock *et al*., 2006), with neither approach distinctly better or worse than the other. Statistical methods, though computationally efficient, are completely dependent on the accuracy of regional temperature, humidity and circulation patterns produced by their parent global models. In contrast, regional climate simulation, though computationally more demanding, can improve the physical realism of simulated regional climate through higher resolution and better representation of important regional processes. The strengths and weaknesses of statistical downscaling and regional modeling are thus complementary.

Strengths and limitations of regional models

We focus here on numerical models simulating regional climate without discussing empirical downscaling because the wide range of applications using the latter undermines making a general assessment of strengths and limitations.

The higher resolution in regional-scale simulations provides quantitative value to climate simulation. With finer resolution, one can resolve mesoscale phenomena contributing to intense precipitation, such as stronger upward motions (Jones *et al*.,1995) and coupling between regional circulations and convection (e.g., Anderson *et al*., 2007). Time-slice AGCMs show intensified storm-tracks relative to their parent model (Solman *et al*., 2003, Roeckner *et al*., 2006). Thus, although regional models may still miss the most extreme precipitation (Gutowski *et al*., 2003, 2007), they can give more intense events that will be smoothed in coarser resolution GCMs. The higher resolution also includes other types of scale-dependent variability, especially short-term variability such as extreme winds and locally extreme temperature that coarser resolution models will smooth and thus inhibit.

Mean fields also appear to be simulated somewhat better on average versus coarser GCMs because spatial variations are potentially better resolved. Thus, Giorgi *et al*., (2001) report typical errors in RCMs of less than 2˚C temperature and 50% for precipitation for regions 10^5–10^6 km^2. Large-scale circulation fields tend to be well simulated, at least in the extratropics.

As alluded to above, regional-scale simulations also have phenomenological value, simulating processes that GCMs either cannot resolve or can resolve only poorly. These include internal circulation features such as the nocturnal jet that imports substantial moisture to the center of the United States and couples with convection (e.g., Byerle and Paegle, 2003; Anderson *et al*., 2007). These processes often have substantial diurnal variation and are thus important to proper simulation of regional diurnal cycles of energy fluxes and precipitation. Some processes require resolving surface features too coarse for typical GCM resolution, such as rapid topographic variation and its influence on precipitation (e.g., Leung and Wigmosta, 1999; Hay *et al*., 2006) and climatic influences of bodies of water like the Gulf of California (e.g., Anderson *et al*., 2001) and the North American Great Lakes (Lofgren, 2004) and their downstream influences. In addition, regional simulations resolve land-surface features that may be important for climate-change impacts assessment, such as distributions of crops and other vegetation (Mearns, 2003; Mearns *et al*., 2003), though care is needed to obtain useful information at higher resolution (Adams *et al*., 2003).

An important limitation for regional simulations is that they are dependent on boundary conditions supplied from some other source. This applies to all three forms of numerical simulation (RCMs, stretched-grid models, time-slice AGCMs), since they all typically require input sea-surface temperature and ocean ice. Some RCM simulations have been coupled to a regional ocean-ice model, with mixed-layer ocean (Lynch *et al*.,1995, 2001) and a regional ocean-circulation model (Rummukainen *et al*., 2004) but this is not common. In addition, of course, RCMs require lateral boundary conditions. Thus, regional simulations by these models are dependent on the quality of the model or observations supplying the boundary conditions. This is especially true for projections of future climate, suggesting that there is value in performing an ensemble of simulations using multiple atmosphere-ocean global models to supply boundary conditions.

Careful evaluation is also necessary to show differences, if any, between the large-scale circulation of the regional simulation and its driving data set. Generally, any tendency for the regional simulation to alter biases in the parent GCM’s large-scale circulation should be viewed with caution (Jones *et al*., 1995). RCM should not normally be expected to correct large-scale circulation problems of parent model, unless there is a clearly understood physical basis for the improvement. Clear physical reasons for the correction due to higher resolution, such as better rendition of physical processes like topographic circulation (e.g., Leung and Qian, 2003), surface-atmosphere interaction (Han and Roads, 2004) and convection (Liang *et al*., 2006), must be established. Otherwise, the regional simulation may simply have errors that counteract the parent GCM's errors, which undermines confidence of projected future climate.

RCMs may also exhibit difficulty in outflow regions of the domain, especially for domains with relatively strong cross-boundary flow, such as extratropical domains covering a single continent or less. The difficulty appears to arise because storm systems may track across the RCM's domain at a different speed than in the driving-data source, resulting in a mismatch of circulations at boundaries where storms would be moving out of the domain. Also, there are always unresolved scales of behavior, so the regional simulations are still dependent on the quality of their parameterizations for the scales explicitly resolved. Finally, the higher computational demand due to shorter time steps limits the length of typical simulations to two to three decades or less (e.g., Christensen *et al*., 2002; NARCCAP, 2007), with few ensemble simulations to date.