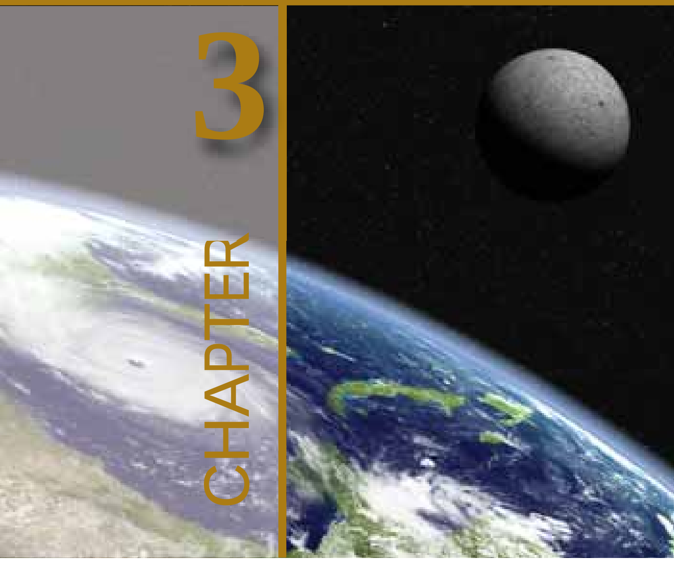


# CHAPTER 3

# Added Value of Regional Climate Model Simulations

## 3.1 TYPES OF DOWNSCALING SIMULATIONS

This section focuses on downscaling using three-dimensional models based on fundamental conservation laws [i.e., numerical models with foundations similar to general circulation models (GCMs)]. A later section of the chapter discusses an alternative method, statistical downscaling.

There are three primary approaches to numerical downscaling:

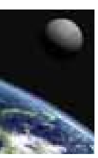
- Limited-area models (Giorgi and Mearns 1991, 1999; McGregor 1997; Wang et al. 2004).
- Stretched-grid models (e.g., Déqué and Piedelievre 1995; Fox-Rabinovitz et al. 2001, 2006).
- Uniformly high resolution atmospheric GCMs (AGCMs) (e.g., Brankovic and Gregory 2001; May and Roeckner 2001; Duffy et al. 2003; Coppola and Giorgi 2005).

Limited-area models, also known as regional climate models (RCMs), have the most widespread use. The third method sometimes is called "time-slice" climate simulation because the AGCM simulates a portion of the period represented by the coarser-resolution parent GCM that supplies the model's boundary conditions. All three methods use interactive land models, but sea-surface temperatures and sea ice generally are specified from observations or an atmosphere-ocean GCM (AOGCM). All three also are used for purposes beyond downscaling global simulations, most especially for studying climatic processes and interactions on scales too fine for typical GCM resolutions.

As limited-area models, RCMs cover only a portion of the planet, typically a continental domain or smaller. They require lateral boundary conditions (LBCs), obtained 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 supplies part of its output back to the parent GCM (Lorenz and Jacob 2005). Simulations with observation-based boundary conditions are used not only to study fine-scale climatic behavior but also to help segregate GCM errors from those intrinsic to the RCM when performing climate change simulations (Pan et al. 2001). RCMs also may use grids nested inside a coarser RCM simulation to achieve higher resolution in subregions (e.g., Liang, Kunkel, and Samel 2001; Hay et al. 2006).

Stretched-grid models, like high-resolution AGCMs, are global simulations but with spatial resolution varying horizontally. The highest resolution may focus on one (e.g., Déqué and Piedelievre 1995; Hope, Nicholls, and McGregor 2004) or a few regions (e.g., Fox-Rabinovitz, Takacs, and Govindaraju 2002). In some sense, the uniformly high resolution AGCMs are the upper limit of stretched-grid simulations in which the grid is uniformly high everywhere.

Highest spatial resolutions are most often several tens of kilometers, although some (e.g., Grell et al. 2000a, b; Hay et al. 2006) have simulated climate with resolutions as small as a few kilometers using multiple 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. Higher resolution generally yields improved climate simulation, especially for fields such as precipitation that have high spatial variability. For example, some studies show that higher resolution does not have a statistically significant advantage in simulating large-scale circulation patterns but does yield better monsoon precipitation forecasts and interannual variability (Mo et al. 2005) and precipitation intensity (Roads, Chen, and Kanamitsu 2003).



Improvement in results, however, is not guaranteed: Hay et al. (2006) find deteriorating timing and intensity of simulated precipitation vs observations in their inner, high-resolution nests, even though the inner nest improves topography resolution. Extratropical storm tracks in a time-slice AGCM may shift poleward relative to the coarser parent GCM (Stratton 1999; Roeckner et al. 2006) or to lower-resolution versions of the same AGCM (Brankovic and Gregory 2001); thus these AGCMs yield 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 much smaller than AOGCM time steps. Increases in resolution most often are applied to both horizontal directions, meaning that computational demand varies inversely with the cube of resolution. Several RCM simulations have lasted 20 to 30 years (Christensen, Carter, and Giorgi 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. Even so, the RCM, stretched-grid, and time-slice AGCM simulations typically last only months to a few years. Vertical resolution usually does not change with horizontal resolution, although 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 also must satisfy numerical constraints. Stretched-grid models whose ratio of coarsest-to-finest resolution exceeds a factor of roughly 3 are likely to produce inaccurate simulation due to truncation error (Qian, Giorgi, and Fox-Rabinovitz 1999). Similarly, RCMs will suffer from incompletely simulated energy spectra and thus loss of accuracy if their resolution is about 12 times or more finer than the resolution of the LBC source, which may be coarser RCM grids (Denis et al. 2002; Denis, Laprise, and Caya 2003; Antic et al. 2004, 2006; Dimitrijevic and Laprise 2005). In addition, these same studies indicate that LBCs should be updated more frequently than twice per day.

Additional factors also govern ingestion of LBCs by RCMs. LBCs are most often ingested in RCMs by damping the model's state toward 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, Marinucci, and Bates 1993). Spurious reflections also may occur in boundary regions (e.g., Miguez-Macho, Stenchikov, and Robock 2005). RCM boundaries should be where the driving data are of optimum accuracy (Liang, Kunkel, and Samel 2001), but placing the buffer zone in a region of rapidly varying topography can induce surface-pressure errors. These errors result from mismatch between the smooth topography implicit in the coarse resolution driving the data and the varying topography resolved by the model (Hong and Juang 1998). Domain size also may influence RCM results. If a domain is too large, the model's interior flow may drift from the large-scale flow of the driving dataset (Jones, Murphy, and Noguer 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 3.1 shows that the daily, root-mean-square difference (RMSD) between simulated and observed (reanalysis) 500-hPa heights generally is within observational noise levels (about 20 m).

Because simulations from the downscaling models may be analyzed for periods as short as a month, model spinup is important (e.g., Giorgi and Bi 2000). During spinup, 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 spinup of soil moisture and temperature, which evolve more slowly. Equally important, data for initial conditions often are lacking or have low spatial resolution, so initial conditions may be only a poor approximation of the model's climatology. Spinup is especially relevant for downscaling because these models presumably are 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 to 2 meters, may require several years of spinup. However, these deep layers generally interact weakly with the rest of the model, so shorter spinup times are used. For multiyear simulations, a period of 3 to 4 years appears to be the minimal requirement (Christensen 1999; Roads et al. 1999). This ensures that the upper meter of soil has a climatology in further simulations that is consistent with the evolving atmosphere.

Many downscaling simulations, especially with RCMs, are for periods much shorter than 2 years. Such simulations probably will not use

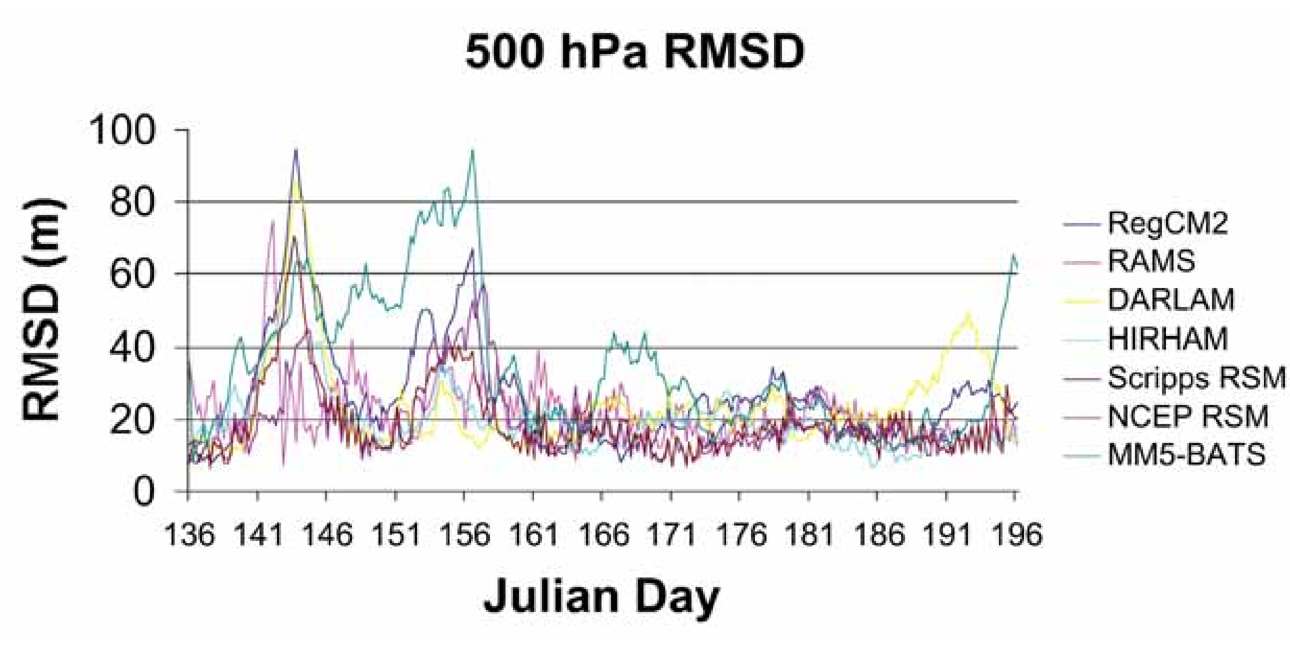


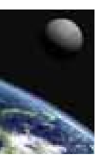

**Figure 3.1. Daily Root-Mean-Square Differences (RMSD) in 500-hPa Heights Between Observations (Reanalysis) and Seven Models Participating in the PIRCS 1a Experiment, for May 15 to July 15, 1988.**

RMSD values were averaged over the simulation domain inside the boundary-forcing zone. [Adapted from Fig. 4 in E.S. Takle et al. 1999: Project to Intercompare Regional Climate Simulations (PIRCS): Description and initial results. *J. Geophysical Research,* **104**, 19443–19461. Used with permission of the American Geophysical Union.]

multiyear spinup. Rather, these studies may focus on more rapidly evolving atmospheric behavior governed by LBCs, including extreme periods such as drought (Takle et al. 1999) or flood (Giorgi et al. 1996; Liang, Kunkel, and Samel 2001; Anderson, C. J., et al. 2003). Thus, they assume that 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, Mo, and Nogués-Paegle 1996), soil moisture (e.g., Xue et al. 2001), or horizontal moisture flux at lateral boundaries (e.g., Qian, Tao, and Lau 2004).

### 3.1.1 Parameterization Issues

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, although a few have used sufficiently fine grid spacing (a few kilometers) to allow acceptable simulation without it (e.g., Grell et al. 2000). Often, these parameterizations are the same or nearly the same as those used in GCMs. All parameterizations, however, make assumptions that they are representing the statistics of subgrid processes. Implicitly or explicitly, they require that the grid box area in the real world has sufficient samples to justify stochastic modeling. For some parameterizations such as convection, this assumption becomes doubtful when grid boxes are 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 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 for 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 better simulates the propagation of precipitation over the U.S. Great Plains that is controlled by large-scale tropospheric forcing, while the Kain–Fritsch scheme better simulates late-afternoon convection peaks in the southeastern United States 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, 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 subgrid process, with multiple choices often available in a single model (e.g., Grell, Dudhia, and Stanfler 1994; Skamarock et al. 2005).

### 3.1.2 Regional Simulation vs Computational Costs

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 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, C. J., et al. 2003; Byerle and Paegle 2003; Pan et al. 2004), and regional ocean-land interaction (e.g., Kim et al. 2005; Diffenbaugh, Snyder, and Sloan 2004). The most immediate value of regional simulation, then, is to explore how such phenomena operate in the climate system, an understanding of 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 balanced between sufficient length and number of simulations for climate statistics vs 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 incorporating 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 boundary-condition source (Pan et al. 2001; de Elía, Laprise, and Denis 2002), although 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 2002; Vidale et al. 2003; Déqué et al. 2005; Liang et al. 2006).

Advances in computing power suggest that typical GCMs eventually will operate at resolutions of most current regional simulations (a few tens of kilometers), so 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, Arritt, and Kain 2007), parameterized behavior not required for resolutions that do not resolve mesoscale circulations.

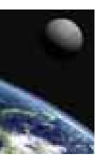
Because of the variety of numerical techniques and parameterizations employed in regional simulation, many models and versions of models exist. Generally in side-by-side comparisons (e.g., Takle et al. 1999; Anderson, C. J., et al. 2003; Fu et al. 2005; Frei et al. 2006; Rinke et al. 2006), no single model appears best vs 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 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 no regional projections have used an ensemble of regional models to simulate the same time periods with the same boundary conditions. Such systematic evaluation has occurred in Europe in the PRUDENCE (Christensen, Carter, and Giorgi 2002) and ENSEMBLES (Hewitt and Griggs 2004) projects and is starting in North America with the North American Regional Climate Change Assessment Program (NARCCAP 2007).

## 3.2 EMPIRICAL DOWNSCALING

Empirical or statistical downscaling is an alternative approach to obtaining regional-scale climate information (Kattenberg 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 targeted area's size can be as small as a single point. As 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, Fock, and Greve 1998) and initiation of flowering (Maak and von Storch 1997). This 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, Zorita, and Cubasch 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 when simple techniques are used. Lower costs, together with flexibility in targeted variables, have led to a wide variety of applications for assessing impacts of climate change.

Some methods have been compared side by side (Wilby and Wigley 1997; Wilby et al. 1998;

Zorita and von Storch 1999; Widman, Bretherton, and Salathe 2003). These studies have tended to show fairly good performance of relatively simple vs more-complex techniques and to highlight the importance of including moisture and circulation variables when assessing climate change. Statistical downscaling and regional climate simulation also have been compared (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 no approach distinctly better or worse than any other. Statistical methods, though computationally efficient, are highly 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 thus are complementary.



## 3.3 STRENGTHS AND LIMITATIONS OF REGIONAL MODELS

We focus here on numerical models simulating regional climate but do not discuss empirical downscaling because the wide range of applications using the latter makes difficult a general assessment of strengths and limitations.

The higher resolution in regional-scale simulations provides quantitative value to climate simulation. With finer resolution, scientists can resolve mesoscale phenomena contributing to intense precipitation, such as stronger upward motions (Jones, Murphy, and Noguer 1995) and coupling between regional circulations and convection (e.g., Anderson, Arritt, and Kain 2007). Time-slice AGCMs show intensified storm tracks relative to their parent model (Solman, Nunez, and Rowntree 2003; Roeckner et al. 2006). Thus, although regional models may still miss the most extreme precipitation (Gutowski et al. 2003, 2007a), 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 than are those in coarser GCMs because spatial variations potentially are better resolved. Thus, Giorgi et al. (2001) report typical errors in RCMs of less than 2˚C temperature and 50% for precipitation in regions 105 to 106 km2. 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, Arritt, and Kain 2007). These processes often have substantial diurnal variation and thus are important to proper simulation of regional diurnal cycles of energy fluxes and precipitation. Some processes require the resolution of surface features too coarse for typical GCM resolution. These include rapid topographic variation and its influence on precipitation (e.g., Leung and Wigmosta 1999; Hay et al. 2006) and the climatic influences of bodies of water such as 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 impact assessments such as distributions of crops and other vegetation (Mearns 2003; Mearns et al. 2003), although care is needed to obtain useful information at higher resolution (Adams, McCarl, and Mearns 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, and time-slice AGCMs), since they all typically require input of 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; Lynch, Maslanic, and Wu 2001) and a regional ocean-circulation model (Rummukainen et al. 2004), but this is not common. In addition, of course, RCMs require LBCs. Thus, regional simulations by these models are dependent on the model quality or on observations supplying boundary conditions. This is especially true for projections of future climate, suggesting value in performing an ensemble of simulations using multiple atmosphere-ocean global models to supply boundary conditions, thus including some of the uncertainty involved in constructing climate models and projecting future changes in boundary conditions.

Careful evaluation also is necessary to show differences, if any, between the regional simulation's large-scale circulation and its driving dataset. Generally, any tendency for the regional simulation to alter biases in the parent GCM's large-scale circulation should be viewed with caution (Jones, Murphy, and Noguer 1995). An RCM normally should not be expected to correct large-scale circulation problems of the parent model unless the physical basis for the improvement is clearly understood. 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, thus undermining confidence in projected future climate.

RCMs also may exhibit difficulty in outflow regions of domains, especially regions with relatively strong cross-boundary flow, which may occur in 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 from their movement in the driving-data source, resulting in a mismatch of circulations at boundaries where storms would be moving out of the domain. Also, unresolved scales of behavior are always present, so regional simulations are still dependent on parameterization quality for the scales explicitly resolved. Finally, higher computational demand due to shorter time steps limits the length of typical simulations to 2 to 3 decades or less (e.g., Christensen, Carter, and Giorgi 2002; NARCCAP 2007), with few ensemble simulations to date.