Use of Limited Area Models to Develop Regional Climate Scenarios

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ABSTRACT

We describe the first simulation experiment and output archives of the Project to Intercompare Regional Climate Simulations (PIRCS). Initial results from simulations of the summer 1988 drought over the central U.S. indicate that limited-area models forced by large-scale information at the lateral boundaries are able to reproduce bulk temporal and spatial characteristics of meteorological fields. In particular, the 500 hPa height field's time average and temporal variability are generally well simulated by all participating models.

Model simulations of precipitation episodes vary depending on the scale of the relevant dynamical forcing. Organized synoptic-scale precipitation systems are simulated deterministically in that precipitation occurs at close to the same time and location as observed (though the amounts may vary from the observations). Episodes of mesoscale and convective precipitation are represented in a more stochastic sense, with less precise agreement in temporal and spatial patterns. Differences in daily maximum temperatures are linked to the Bowen ratio differences, indicating strong local, surface influence on this field. Although some of the models have bias with respect to the FIFE observations, they all tend to reproduce the synoptic variability of observed daily maximum and minimum temperatures.

1. Introduction

Knowledge of climate variability in sub-continental regions is important for understanding impacts of potential climate change. For this reason much attention has been devoted in recent years to climate simulation using limited-area atmospheric models driven by output from a coarser resolution global model or, for test purposes, an atmospheric analysis. The overall strengths and weaknesses of this approach to climate simulation have been difficult to assess because the disparate applications[1,2] lack a common framework.

The Project to Intercompare Regional Climate Simulations (PIRCS) was developed to provide a common simulation framework for evaluating mesoscale models run in climate mode, both versus each other and versus observations. PIRCS has developed with strong community involvement, through a series of workshops[3,4] and additional informal exchanges among participants and advisors. Here we describe some preliminary results from the first experiment that give an initial indication of the collective capabilities of the participating models and of this approach to climate simulation. Additional details can be found at the PIRCS Web site, http://www.pircs.iastate.edu.

2. PIRCS Experiment 1

(a) Domain and period

The simulation domain for Experiment 1 covers the continental United States with a specific focus on the central region. Simulations cover two periods of hydrologic extremes in the central US: 15 May - 15 July 1988 (drought) and 1 June - 31 July 1993 (flood). These periods were chosen to give strong signals of climate variability that a model should be able to capture. Summer periods were chosen because large-scale circulation is typically weaker in summer, so that local, mesoscale circulation might be expected to play a larger role in regional climate. This places a greater challenge on the models to generate regional climate internally without strong external control through lateral boundary conditions. Periods of only two months were initially chosen to balance limitations in computational and personnel resources for a largely volunteer effort against the need for simulations long enough to capture climatic behavior.

A fundamental assumption in PIRCS is that there must be important mesoscale features in the targeted domain for climate simulation by a mesoscale model to give added value to the global simulation driving it. The central United States contains a significant mesoscale circulation, the nocturnal, low-level jet [LLJ]. The LLJ exhibits a strong diurnal cycle, with maximum flow tending to occur in the middle of the night[5,6]. The LLJ plays an important role in the development and sustenance of mesoscale convective precipitation systems, which typically provide about half of the growing-season precipitation over the central U.S.[7].

The central U.S. was also chosen because it contains a dense climatic observing network whose measurements can be used to assess model performances. This region has also experienced field campaigns such as the First ISLSCP Field Experiment (FIFE)[8] and new instrument networks such as wind profilers[9] that provide additional observations. Finally, partly for the same reasons as given here, the central U.S. is the focus region for the Global Energy and Water Experiment's Continental International Project[10]. One goal of GCIP is to improve simulation of climatic water and energy cycles. PIRCS is helping GCIP attain this goal by providing a framework for assessing mesoscale model simulation of these cycles.

(b) Initial and boundary conditions

Atmospheric initial and boundary conditions were extracted from the reanalysis produced by the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR)[11]. We treated the reanalysis as output from a "perfect" model of the atmosphere for the periods simulated and thus conservatively assumed that differences between model output and observed behavior represent errors in the simulations due to factors such as construction of boundary conditions and internal shortcomings in the models. This assumption is most reasonable for large-scale mass, temperature and momentum fields and less so for humidity[12].

The initial and boundary conditions used the finest output resolution available, sigma-layer fields on the T62 gaussian grid of the data assimilation cycle's forecast model. Horizontal interpolation was performed to produce driving files matching or nearly matching the standard PIRCS resolution of 60 km. A small degree of additional interpolation was needed to transfer the initial and boundary conditions files to forms actually ingested by individual models. The oceanic portions of the simulation domain used sea-surface temperatures (SSTs) derived from the reanalysis SST data set. These were supplemented by direct observations of surface temperature in the Great Lakes and satellite observations of SST in the Gulf of California, where the reanalysis grid gave only crude resolution.

The most problematic initial condition was soil moisture. Over most of the PIRCS domain, this field is not observed regularly, necessitating use of an indirectly estimated soil moisture field. Furthermore, because the spin-up time for soil moisture simulation is probably several weeks or months, any errors in initial soil moisture will persist throughout the two simulation periods. For consistency with the atmospheric driving conditions, PIRCS used the soil moisture produced by the surface parameterization of the reanalysis forecast model. The reanalysis soil moisture is subject to relaxation toward an estimated annual climatology[13] and thus must be viewed with caution as an initial condition.

(c) Output archive

A general goal of the archive is to permit analysis of key mesoscale features, such as the low-level jet, and energy and water cycles linked to mesoscale behavior. Therefore most fields are saved at least four times daily to allow analysis of diurnal variability. An additional goal has been to have a relatively simple archive to minimize the potential for confusion and mistakes in creating it and to promote archive accessibility. Archived output will be available to the general community, though interested users are required to maintain contact with PIRCS and participating modelers to ensure clear understanding of what the models can and cannot do.

(d) Participating models

Participation in PIRCS is currently open to all modeling groups willing to perform the simulations and furnish the output in a standard format. For this initial report, output is available from seven models. Results presented here are based on output selected from the models' contributions to the PIRCS archive for the 1988 PIRCS simulation.

3. Initial results for the 1988 drought

(a) 500 hPa height field

We used the NCEP reanalysis as a standard for evaluation of the 500 hPa height field. Time-average 500 hPa heights from the reanalysis for 15 May - 15 July 1988 show that the central U.S. was dominated by a large-scale ridge[14,15]. We evaluate the models using the root-mean-square difference (RMSD) of the predicted 500 hPa height field from that in the reanalysis.

The temporal trend of the spatially-averaged RMSD (Figure 1) shows that most models exhibit a base level of RMSD around 10-20 m with occasional episodes of higher values. There was a period about 5 to 10 days after the start of the simulation (Julian days 140-145; May 20-25) when the RMSD was relatively large for most models. During this time a strong 500 hPa closed low slowly migrated across the U.S. For Julian days 158-186 the RMSD was near minimum for all models. This was a period characterized by the gradual breakdown, partial redevelopment, and continued breakdown of an intense mid- and upper-tropospheric ridge over the central U.S. Near the end of the simulation there was an episode when RMSD increased for RegCM2 and DARLAM. The increased RMSD corresponded with the development and migration of a weak trough across the central U.S. In a broad sense the models appear to handle development and breakdown of large-scale ridges well and the evolution of short-wavelength lows somewhat less well; however, there are substantial variations from model to model and from case to case.

(b) Precipitation

Evaluation of simulated precipitation uses gridded observations of Higgins et al.[16] for comparison.

These observations are analyzed onto a fairly coarse grid (2^o latitude by 2.5^o longitude). While the mesoscale features of the precipitation distribution are thus averaged out, the analysis provides a basis for assessing broad features of the precipitation distribution. Analysis of predicted precipitation focuses on a portion of the Upper Mississippi River basin (37 N - 47 N, 89 W - 99 W) that is well resolved by the PIRCS models (about 400 grid points) but poorly resolved by a GCM or the reanalysis. Two prominent episodes occurred during the experiment period: Julian days 139 - 158, dominated by large-scale, synoptic systems and Julian days 164 - 178, primarily local variability, especially in precipitation. During the former episode, external boundary conditions should exert substantial influence through their guidance of large-scale flow. During the latter episode, external forcing should be weak, with much if not most of the simulated precipitation appearing as quasi-random convection.

Although the models differ in precipitation magnitudes, they do capture the frequency of synoptically forced precipitation (Figure 2), particularly for the four precipitation events during the episode dominated by large-scale, synoptic systems (Julian days 139 - 158). Equally important for hydrologic considerations, the models also capture dry periods with reasonable fidelity during this episode. All models thus effectively ingest influences of large-scale, lateral boundary forcing on precipitation. For Julian days 164 - 178, the observed precipitation is frequent in small amounts, with no clearly definable precipitation events. The models represent this stochastic behavior well, although again they differ from each other and the observations in precipitation magnitude.

The isolated precipitation event on Julian day 160 is particularly noteworthy. This was a transient event within an overall dry period created by a strong omega block, during which a well-defined precipitation region (likely a mesoscale convective system) migrated across the evaluation subdomain. This event is particularly revealing because its limited spatial and temporal existence 15 days from model initialization and far from forcing boundaries offers challenges for models to simulate. The models capture the existence of this episode quite well, including its temporal isolation within a generally dry period, although as before, some difficulty is noted for individual models in getting the correct precipitation amount.

These preliminary results suggest that regional models run in climate mode are capable of transporting remotely introduced water vapor and producing precipitation that, on average, matches observed spatial and temporal patterns reasonably well.

(c) Daily minimum and maximum temperature

An important outcome of surface-atmosphere interaction and synoptic weather fluctuations is the time variation of daily minimum and maximum temperature. Here we compare the models to observations from the FIFE experiment.[17]. For daily maximum temperature (Figure 3), the models tend to follow the temperature's synoptic-scale variability, though with bias. Most models, for example, captured sharp decreases and increases in temperature around days 142, 167, and 183. Model bias in maximum temperature tends to vary with the mid-day, time-average Bowen ratios. The coolest maxima occur for MM5-BATS and HIRHAM, which have the smallest Bowen ratio, whereas DARLAM has the warmest maxima as well as the largest Bowen ratio. Maximum temperature evolution thus shows evidence of external control by the synoptic flow and local control by surface energy balances.

Daily minimum temperature (Figure 4) also tends to reproduce the synoptic variability of the FIFE observations. Model-observation differences tend to be smaller in magnitude compared to the daily maximum temperature differences. In contrast to the temperature maxima, however, model-to-model differences in minimum temperature show less relationship to simulated surface energy balances. Although DARLAM still has the largest positive bias versus FIFE observations, there is otherwise no consistent relationship between Bowen ratio and minimum temperature. This of course is not surprising since minimum temperatures tend to occur at night in the models (as they do in the observations; not shown), when the surface fluxes shown are weak.

4. Summary

Limited-area models forced by large-scale information at the lateral boundaries are able to reproduce the bulk temporal and spatial characteristics of meteorological fields during the 1988 drought. The mean 500 hPa height field is generally well simulated, as is its temporal variability. There is some evidence that model skill varies with the synoptic regime in a common way. Specifically, situations dominated by a ridge or zonal flow are well simulated by most models as measured by the root-mean-square deviation from the reanalysis, while situations characterized by development and migration of short-wave lows or troughs tend to have larger RMSD.

Model simulations of precipitation episodes vary depending on the scale of the relevant dynamical forcing. Organized synoptic-scale precipitation systems are simulated deterministically, in that precipitation occurs close to the same time and location as observed (though the amounts may vary from the observations). Episodes of mesoscale and convective precipitation are represented in a more stochastic sense: general periods of scattered convective precipitation tend to be captured in the models, though with less precise agreement in temporal and spatial patterns than for the synoptically organized events. Differences in daily maximum temperatures are linked to the Bowen ratio differences, indicating strong local, surface influence on this field. Although some of the models have bias with respect to the FIFE observations, they all tend to reproduce the synoptic variability of observed daily maximum and minimum temperatures.

Although there are some common strengths and deficiencies among the models, no single model stands out as best in all comparisons. Rather, each model has individual strengths and deficiencies in addition to characteristics of the ensemble output. This feature illustrates the importance of archiving a variety of output fields that can be compared with observations. Furthermore, in keeping with the goals of PIRCS, the side-by-side assessments here help highlight more clearly specific areas where modeling groups individually and collectively may want to focus efforts to improve model performance.

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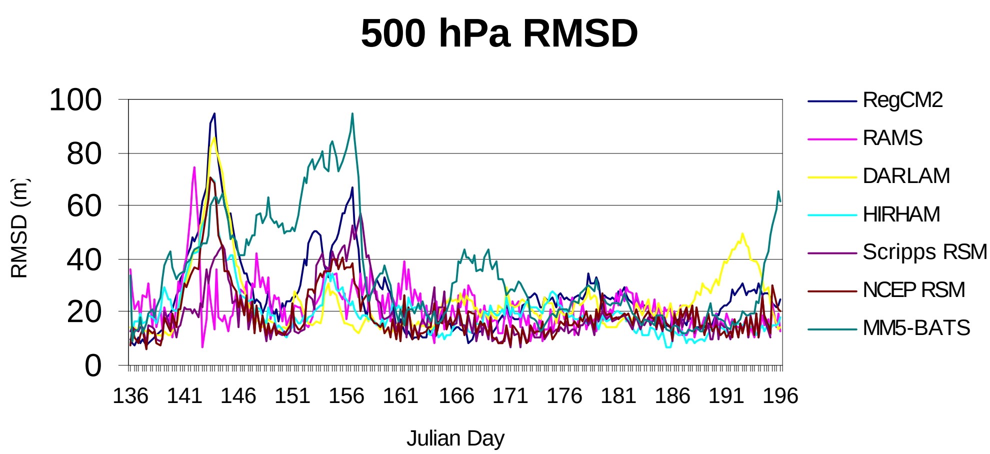
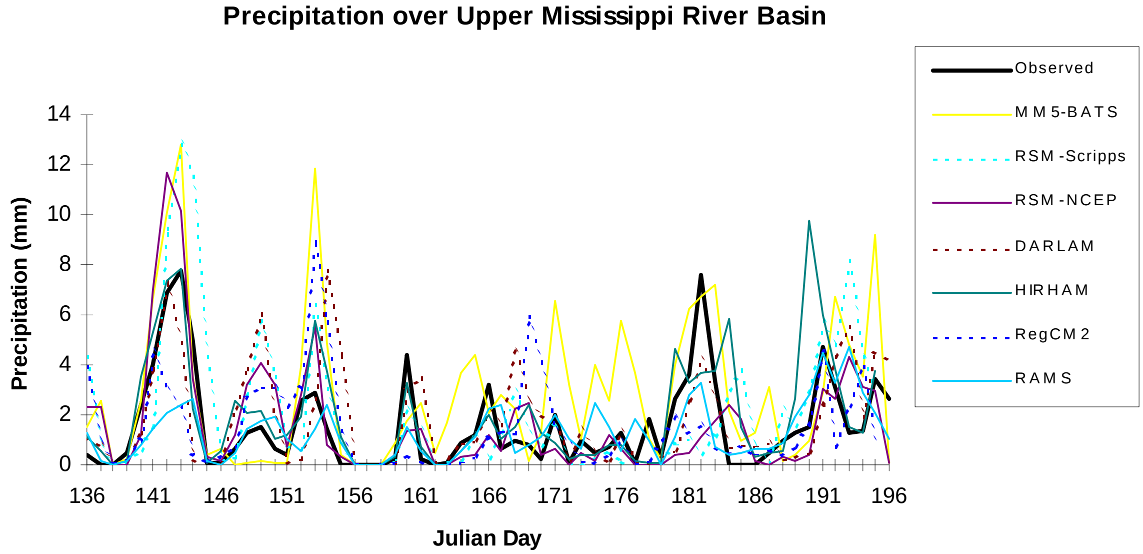
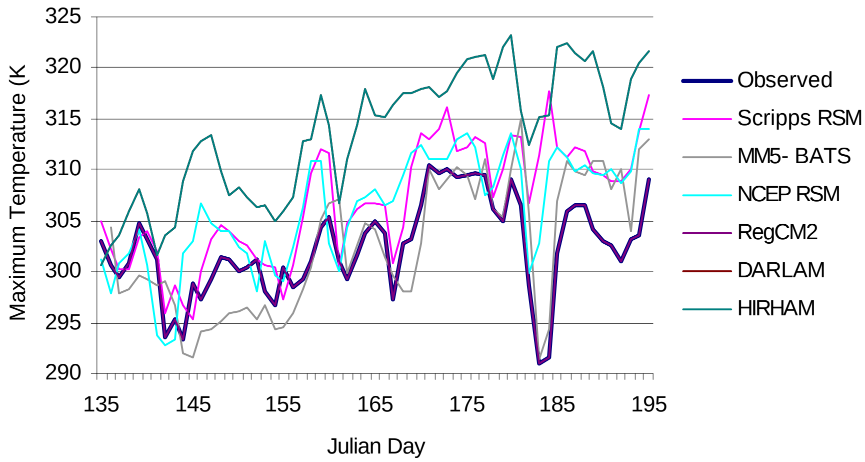
FIGURES



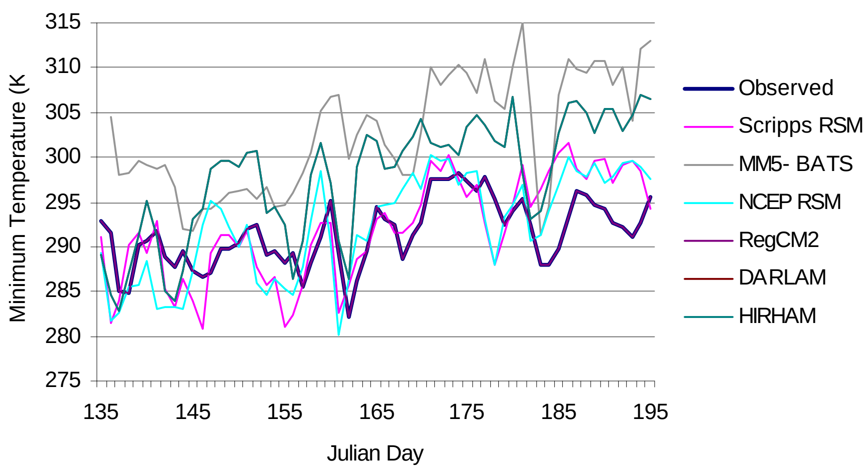
1. Time series of spatially averaged root-mean-square deviation of predicted 500 hPa heights compared with the NCEP/NCAR reanalysis.



2. Time series of predicted precipitation over a portion of the upper Mississippi River basin (37-47 ^{o}N, 89-99^{o}W) compared with observations.



3. Time series of daily maximum temperature from FIFE observations processed by Betts and Ball (1998) and from each model's gridpoint nearest the FIFE site.



4. Like Fig. 3, but for daily minimum temperature.