The Effects of Domain Choice on Summer Precipitation Simulation and Sensitivity in a Regional Climate Model

ANJI SETH AND FILIPPO GIORGI

National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 12 June 1997, in final form 5 December 1997)

ABSTRACT

Recent results show disagreement between global and limited-area models as to the role of soil moisture feedback during the summer of 1993 in the central United States. July precipitation totals increase by 50% in the European Centre for Medium-Range Weather Forecasts global model when soil moisture is initialized ''wet,'' but two separate regional modeling groups [University of Utah Limited Area Model group and National Center for Atmospheric Research Regional Climate Model (RegCM) group] have found very different responses to soil moisture, indicating that drier soil moisture conditions might actually lead to increased precipitation via an increase in convective instability and an enhancement of the low-level jet from the Gulf of Mexico.

To further evaluate the sensitivity results of RegCM in this context, a new suite of simulations, driven by analyses of observations for May–July of 1988 and 1993 is performed. The model domain is larger than in the previous experiments and the sensitivity of predicted seasonal rainfall to ''wet'' and ''dry'' initial soil moisture is analyzed. In comparing the new simulations with the earlier results, it is found that the simulation of seasonal precipitation as well as its sensitivity to initial soil moisture are affected by domain size and location of the lateral boundaries in both the 1988 and 1993 experiments. The smaller domain captures observed precipitation better in the upper Mississippi basin; however, the sensitivity of precipitation to initial soil moisture appears to be more realistic in the larger domain. While the lateral boundary forcing in the small domain experiments constrains the model to a better overall simulation, it also yields an unrealistic response to internal forcings, which are not consistent with the applied large-scale forcing. These results demonstrate that the domain of a regional climate model must be carefully selected for its specific application. In particular, domains much larger than the area of interest appear to be needed for studies of sensitivity to internal forcings.

1. Introduction

Regional climate models (RegCMs) have been recently developed for simulations of monthly to decadal timescales (Dickinson et al. 1989; Giorgi 1990; Cullen 1993). RegCMs are run over limited-area domains and are driven by time-dependent large-scale meteorological fields specified in a buffer area adjacent to the domain's lateral boundaries. These fields can be provided either by analyses of observations or by output from general circulation model simulations. After a spinup time of a few days, the solution in the interior of a RegCM domain is essentially the result of a dynamical equilibrium between lateral boundary forcing and internal model forcing (Anthes et al. 1989). As the ratio of the lateral buffer area to the size of the domain decreases, the interior domain solution tends to increasingly diverge from the forcing large-scale fields (Jones et al. 1995). In addition, the location of the boundaries in relation to the regions that provide the strongest sources of forcing in a particular climatic regime can also affect a regional model simulation.

In this paper we present a study of the effect of model domain on seasonal, summertime precipitation simulation and its sensitivity to initial soil moisture. The simulated periods are May–July (MJJ) of 1988 and (MJJ) 1993 over the central United States. The summer of 1988 was marked by a pronounced drought event over the region, whereas the summer of 1993 was characterized by extended flood conditions. The motivation for this study originated from the discordant results obtained by three previous studies, those of Beljaars et al. (1996), Paegle et al. (1996), and Giorgi et al. (1996) (hereafter referred to as B96, P96, and G96, respectively), who looked at the sensitivity of simulated precipitation to surface soil wetness for the summer of 1993 over the central United States. In these three studies, the simulated soil moisture feedbacks varied from strong positive, to strong negative, to generally weak.

In B96, the European Centre for Medium-Range Weather Forecasts (ECMWF) global model simulated an increase of 50% precipitation over the upper Mississippi basin (UMB) when the soil was initialized wet. Local soil moisture was thus a critical factor in maintaining the simulated flood conditions. Conversely, P96

Corresponding author address: Anji Seth, NCAR/CGD, 1850 Table Mesa Drive, Boulder, CO 80307.
E-mail: seth@ncar.ucar.edu

reported a 50% decrease in precipitation when upstream evaporation was high in simulations employing the University of Utah Limited Area Model (LAM). Finally, G96 found little sensitivity to initial soil moisture in simulations employing the National Center for Atmospheric Research (NCAR) RegCM. Therefore, in P96 and G96 the local soil moisture control was not critical for the maintenance of the flood conditions.

Although the models used by B96, P96, and G96 utilized different physics parameterizations, the most obvious difference between these experiments was in the model domain: B96 used a global domain, while P96 and G96 used limited-area domains of relatively small size encompassing the UMB region. The discordance of these results may thus be an indication that the interactions between boundary conditions and internal model forcings played an important role not only in the actual simulation of the events, but also in the model sensitivity to soil moisture forcing. Driven by these considerations, we decided to further evaluate the effects of local (soil moisture) versus remote (large-scale circulations) controls of the summer 1988 and 1993 events with the NCAR RegCM.

In the present study, the model and simulated periods are the same as in G96, but the domain size is much larger, encompassing the whole continental United States landmasses and surrounding ocean waters. Simulations of MJJ 1988 and MJJ 1993 are completed both with a wet and a dry soil moisture initialization, and results are compared with those of G96 and, for the summer of 1993, B96 and P96. In the next section we first briefly review the main circulation features that characterized the summer 1988 and 1993 events over the United States along with the primary physical processes underlying the results of B96, P96, and G96. Section 3 describes the model and experiment design for the present study, and section 4 presents the simulation results. A discussion of the results is given in section 5, and conclusions of this work are presented in section 6.

2. Background

a. *Observations of the summers of 1988 and 1993 over the continental United States*

Observed MJJ precipitation totals for 1988 and 1993 over the continental United States are given in Fig. 1. This gridded precipitation is derived from National Climate Data Center (NCDC) monthly mean precipitation values from approximately 350 stations. The UMB region, for which detailed precipitation and evaporation statistics are analyzed in this paper, is depicted by a black box in Fig. 1a. The difference in observed precipitation for the two years is dramatic. In 1988, only a few areas received more than 200 mm of rainfall for MJJ. In 1993 most of the central and northwestern United States saw at least 200 mm of rainfall, and the central and upper Mississippi basin received over 500 mm and up to 700 mm. In the UMB region, observations show a factor of 3 increase in precipitation between 1988 and 1993 (1.84 vs 5.62 mm day^{-1}).

The large-scale conditions over North America were distinctly different in 1988 and 1993 as discussed by Trenberth and Guillemot (1996). In 1988 a relatively strong anticyclonic pattern over North America, east of the Rocky Mountains, as seen in the upper-level winds, displaced the midlatitude jet well north of its climatological summertime position and into Canada. In addition, analyzed mean vertically integrated moisture transport shows significantly enhanced northward transport of moisture from the Gulf of Mexico into the central United States in 1993 compared to 1988. These large-scale features are considered primarily responsible for the anomalous MJJ precipitation. In 1988, weak moisture transport from the Gulf and northward displacement of the jet resulted in severely dry conditions; whereas in 1993 a large moisture supply from the Gulf and southward displacement of the jet resulted in severe flooding in the Mississippi basin. Within the context of these large-scale conditions there is uncertainty concerning the role of land surface evapotranspiration. Three recently published numerical studies highlight this uncertainty (see Table 1) and are discussed in the following paragraphs.

b. *Mechanisms given in B96, P96, and G96*

Significant improvement in simulated precipitation for July 1993 was found in the ECMWF global model when soil moisture was prognostically calculated rather than prescribed from climatological values (Beljaars et al. 1996). In addition, realizations of 30-day simulations for July 1993 with the modified model using wet and dry initial soil conditions demonstrate a 50% increase in precipitation in the runs initialized wet. Analysis reveals that enhanced evaporation approximately one day upstream (northern Mexico and Texas) modifies the thermodynamic structure of the boundary layer in the upper Mississippi basin. This mechanism is described schematically in the top panels of Fig. 2. In the case of reduced upstream surface evaporation, the transport of warm dry air aloft creates a stable boundary layer inversion that inhibits convection. Increased upstream evaporation results in the transport of cooler, more moist air (higher θ_e), which removes the capping inversion and permits deep precipitating convection.

Paegle et al. (1996) report a 50% decrease in precipitation when upstream evaporation is high in 14-day simulations (27 June–10 July 1993) employing the University of Utah LAM. These simulations incorporate wet and dry values of evaporation, which are fixed for the duration of the simulations. The mechanism for this result, as revealed by the authors, is as follows: reduced surface evaporation yields warmer daytime surface conditions, which lead to greater low-level buoyancy and

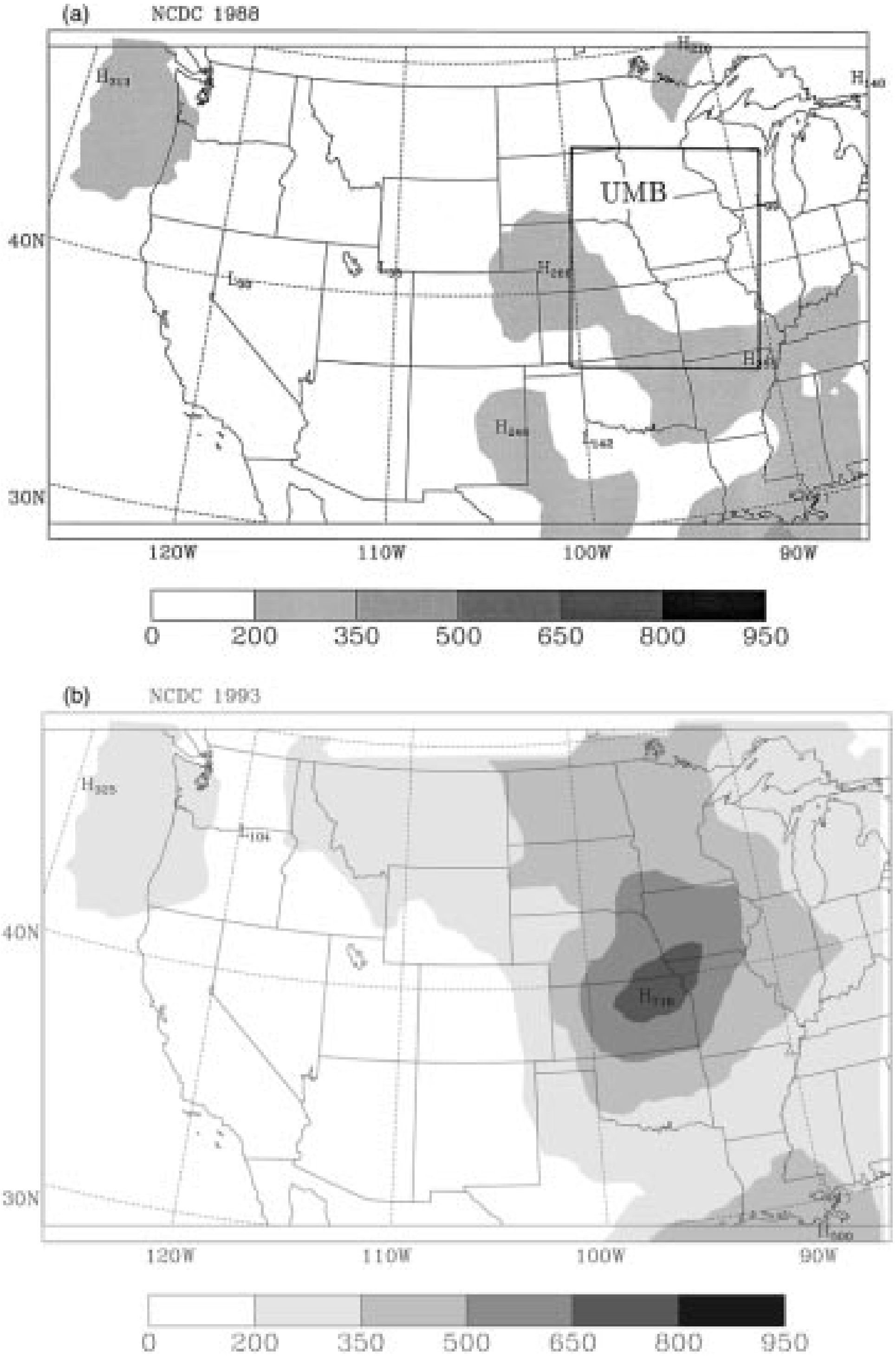


FIG. 1. Observed MJJ rainfall totals (mm) for (a) 1988 and (b) 1993 over the continental United States, analyzed from NCDC monthly mean station data. The Upper Mississippi Basin (UMB) region is defined by the box in (a).

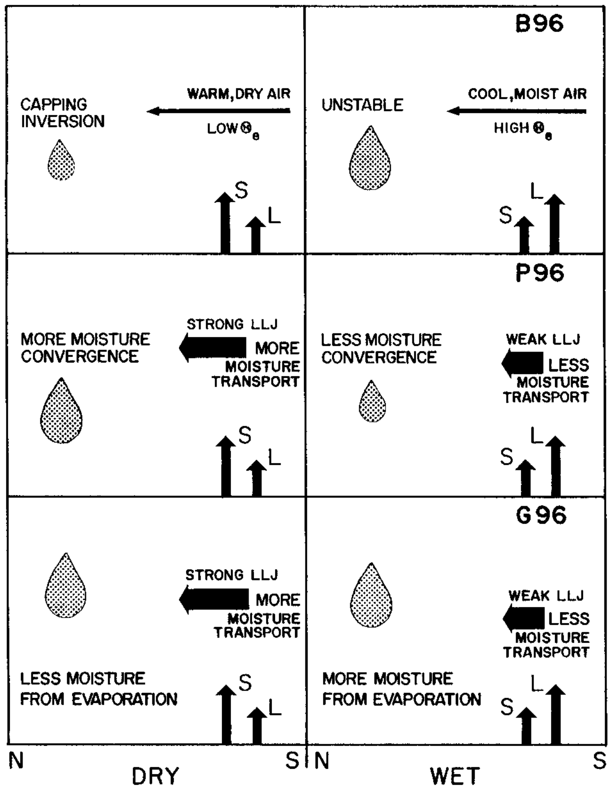


FIG. 2. Schematic description of mechanisms that relate simulated precipitation to surface evaporation in Beljaars et al. (1996) (B96), Paegle et al. (1996) (P96), and Giorgi et al. (1996) (G96). The abbreviations LLJ, S, and L represent the low-level jet, and surface fluxes of sensible and latent heat, respectively.

produce a stronger low-level jet (LLJ). The enhanced LLJ transports more moisture from the Gulf of Mexico into the central plains, and the increased moisture convergence in the UMB triggers the LAM convection scheme and results in enhanced precipitation. See the middle panels of Fig. 2.

The third study employs the NCAR Regional Climate Model (RegCM) in a series of 100-day simulations 22 April–30 July 1993 and 1988). The authors (Giorgi et al. 1996) found little sensitivity of seasonal precipitation to initial soil moisture. The small sensitivity they did find showed that decreased evaporation thermally and dynamically supports convection and increases precipitation in the UMB, particularly in 1988. The bottom panels of Fig. 2 illustrate this mechanism schematically. When evaporation is reduced, the LLJ is enhanced and transports more moisture from the Gulf of Mexico. In addition, increased surface sensible heat flux increases buoyant energy production. These two effects compensate for the reduction in the evaporative moisture source so that precipitation is affected minimally.

Interestingly, the regional model sensitivity results (P96 and G96) both demonstrate an enhanced LLJ in the simulations initialized with dry soil, whereas the global model (ECMWF) did not produce a stronger LLJ in the dry simulations (P. Viterbo 1997, personal communication). In addition, the limited-area domains used by G96 (2300 km × 3800 km) and P96 (3500 km × 3600 km) (see Fig. 9) both have boundaries in the southeastern United States, relatively near the course of the LLJ.

TABLE 1. Results from model studies that examine the sensitivity of simulated precipitation to soil moisture during the summer of 1993. The studies referred to are Beljaars et al. (1996) (B96), Paegle et al. (1996) (P96), and Giorgi et al. (1996) (G96). Domains #1 and #2 are defined in Fig. 9.

Study	Model	Domain	Period	Sensitivity 1993
B96	ECMWF	global	30 day	+50%
P96	Utah LAM	#1	14 day	−50%
G96	RegCM2	#2	MJJ	+4%

c. Summary of small domain experiments

The four simulations that were analyzed in G96 have been rerun for this study due to an error found in the original RegCM calculation of vegetation cover. The results of the new simulations do not change the conclusions of G96, but the quantitative values of precipitation and surface fields presented in the earlier paper are slightly affected. The simulations are initialized on 22 April and are integrated for 100 days. They are identical to the runs presented in G96 except for a correction in the land surface calculation and will be referred to as the small domain simulations. The domain is 46 × 77 grid points, at 50-km resolution and centered at 40.5°N, 105°W. The simulations are referred to as SMWET93, SMDRY93, SMWET88, and SMDRY88 in Table 2 and refer to different initializations of the soil moisture availability, which is the fraction of water in the column between wilting point and saturation. In the dry initializations of 1988 and 1993 the initial soil water in the column is prescribed to be just above the wilting point of the vegetation (0.01), and in the wet initialization the soil moisture fraction is prescribed initially as a function of vegetation type for spring conditions (approximately 0.8).

The simulations discussed by G96, which have been recomputed for this work, are briefly presented here to document the corrections (which are numerical only and do not change the conclusions of G96) and to compare

TABLE 2. RegCM simulations recomputed with the G96 domain (46 × 77 grid points, centered at 40.5°N, 105°W, 50-km resolution) and ECMWF boundary conditions for this study. SMF is the initial column soil moisture fraction.

Experiment	SMF	Period
SMWET88	~0.8	22 April–30 July 1988
SMDRY88	0.01	22 April–30 July 1988
SMWET93	~0.8	22 April–30 July 1993
SMDRY93	0.01	22 April–30 July 1993

TABLE 3. Results from RegCM simulations recomputed with the G96 domain. MJJ average daily precipitation and evaporation rates are computed for the defined region UMB. Observed precipitation is derived from NCDC monthly mean station data. Observed evaporation is estimated by Trenberth and Guillemot (1996).

	P (mm day^{-1})	E (mm day^{-1})
OBSERVED88	1.84	2.50
SMWET88	2.14	4.12
SMDRY88	2.32	2.12
OBSERVED93	5.62	4.00
SMWET93	5.49	4.10
SMDRY93	5.26	3.63

them with the simulations performed for this study. Statistics computed for the UMB in these simulations are provided in Table 3.

Figure 3 shows the simulated total precipitation (in mm) for MJJ from the SMWET88 and SMWET93 experiments. The model-generated precipitation pattern represents quite well that observed in 1993, although the model appears to be drier than observed in the southern and eastern regions of the model domain and in the northwest. In the UMB the mean daily precipitation rate is 5.49 mm day^{-1}, which is close to the observed value (5.62 mm day^{-1}). In 1988 the simulated precipitation shows a decrease from the 1993 value in the box we have defined as the UMB, but the model generally overpredicts precipitation (2.14 mm day^{-1} vs observed 1.84 mm day^{-1}). If we define the precipitation signal between 1993 and 1988 as the ratio of 1993 over 1988 precipitation values in the UMB, the amplitude of the model precipitation signal between 1988 and 1993 is somewhat smaller than the observed (a factor of 2.6 vs 3). The overall pattern for the domain shows more precipitation than observed in the southeastern region, over Texas and Oklahoma.

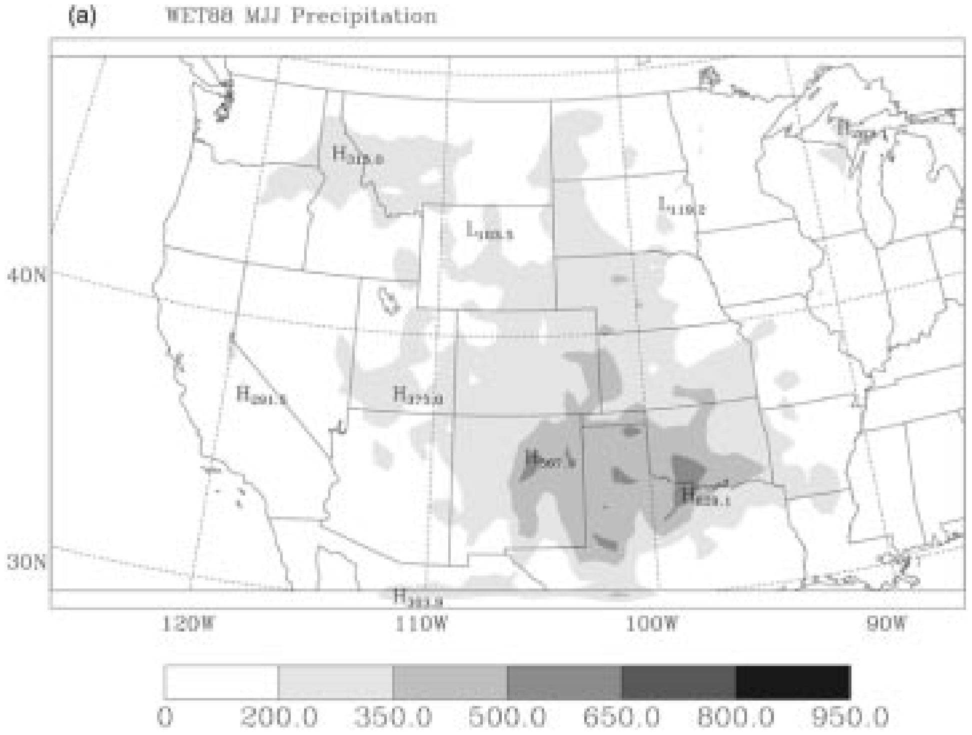
G96 reported 1) very little sensitivity of simulated precipitation to initial soil moisture and 2) what sensitivity was seen showed more precipitation in the runs initialized dry. These results are modified as follows by the corrected model simulations. The sensitivity of precipitation to initial soil moisture is qualitatively illustrated in Figs. 4a, b, where results from SMDRY88 and SMDRY93 are provided. The domain precipitation appears to be reduced in the runs initialized dry in both years, implying a positive soil moisture feedback. However, the effect is not substantial. Thus the G96 assessment of small sensitivity remains intact. The calculations for the UMB in 1993 show very little change in precipitation; there is a 4% decrease in precipitation in response to an 11% decrease in evaporation. The UMB results for 1988 show a negative response to soil moisture or an increase of 8% in precipitation for a decrease of 49% in evaporation. This negative feedback is similar to that reported in G96. However, upon closer inspection it can be seen that the southeastern region of the small domain shows precipitation in excess of that observed in both wet and dry simulations for 1988. The UMB region is located just outside this region of excess precipitation; therefore, the UMB calculation for 1988 is likely to be statistically insignificant. The main conclusion, as given by G96, is that soil moisture in these simulations has very little control over the seasonal precipitation totals. The second conclusion of G96, that is, that the simulated soil moisture feedback is likely to be negative over the UMB (similar to the conclusion of P96), appears less strongly supported by the results and will be discussed in more detail in the next sections.

3. Model description

The RegCM (Giorgi et al. 1993a,b) is a limited-area model whose dynamical component is essentially that of the Penn State–NCAR Mesoscale Model version 4.0 (MM4). The model is hydrostatic, compressible, based on primitive equations, and employs a terrain-following σ-vertical coordinate. Sigma is defined $\sigma = (p - p_{\text{top}})/(p_s - p_{\text{top}})$, where p is pressure, p_{top} is pressure at the uppermost model level, and p_s is surface pressure. The model includes parameterizations of surface, boundary layer, and moist processes, which account for the physical exchanges between the land surface, boundary layer, and free atmosphere. The model has 14 levels with about 5 levels within the planetary boundary layer (below 800 mb). The model top is at 80 mb. A brief description of the surface, boundary layer, and convective parameterizations is presented here, which is sufficient for our analysis and later discussion. Further details are available in the references.

The bottom boundary is comprised of land and ocean in the regional model domain. Surface–atmosphere exchange fluxes are computed using the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1993). Each atmospheric model grid point is specified with characteristics for a single vegetation and soil class. Air temperature, humidity, pressure, winds, radiation, and precipitation are provided by the atmospheric model to BATS at each domain grid point. For grid points designated as land, BATS computes surface radiative, sensible and latent heat, momentum fluxes, and surface temperature based on the assigned vegetation and soil parameters. The exchange between atmosphere and ocean is also computed by BATS, with sea surface temperatures specified from a dataset of monthly mean values (Reynolds 1988).

The effects of boundary layer turbulence and associated vertical transport are considered in the RegCM using a formulation developed by Holtslag et al. (1990) and Holtslag and Boville (1993). This is a medium-resolution scheme with five levels in the lowest 1.5 km of the atmosphere, at approximately 40, 110, 310, 730, and 1400 m above the surface. The vertical eddy flux within the PBL is given by an eddy-diffusion term plus a ‘‘countergradient’’ term describing nonlocal transport due to deep convective plumes in the PBL. The eddy



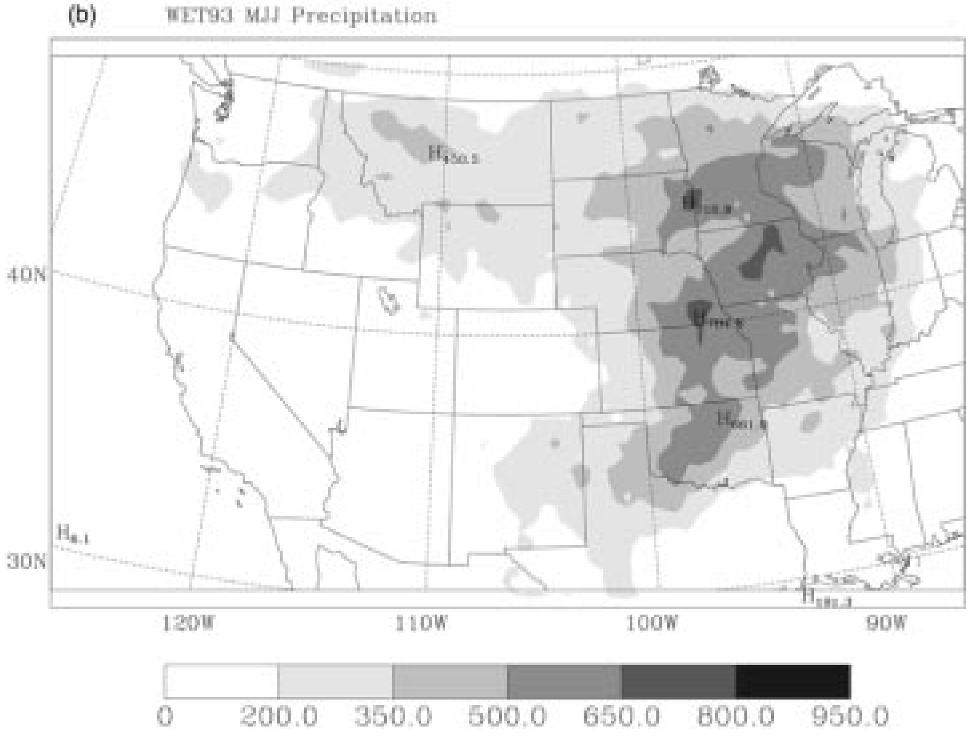
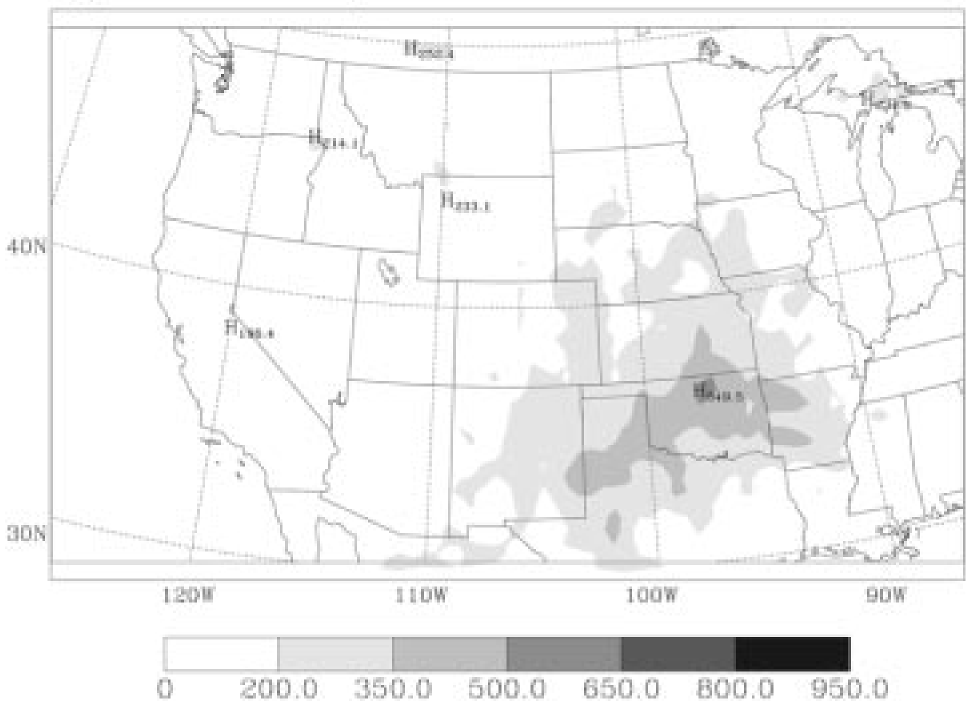


FIG. 3. Simulated MJJ rainfall totals (mm) for (a) SMWET88 and (b) SMWET93.

diffusivity follows a parabolic profile between the surface and the PBL top.

Resolvable-scale precipitation is treated with a simplified version of the explicit moisture scheme of Hsie et al. (1984), as described by Giorgi and Marinucci (1996). This scheme includes only an equation for cloud water, which is formed when supersaturation is attained. It is then advected and can be re-evaporated, or con-

(a) DRY88 MJJ Precipitation



(b) DRY93 MJJ Precipitation

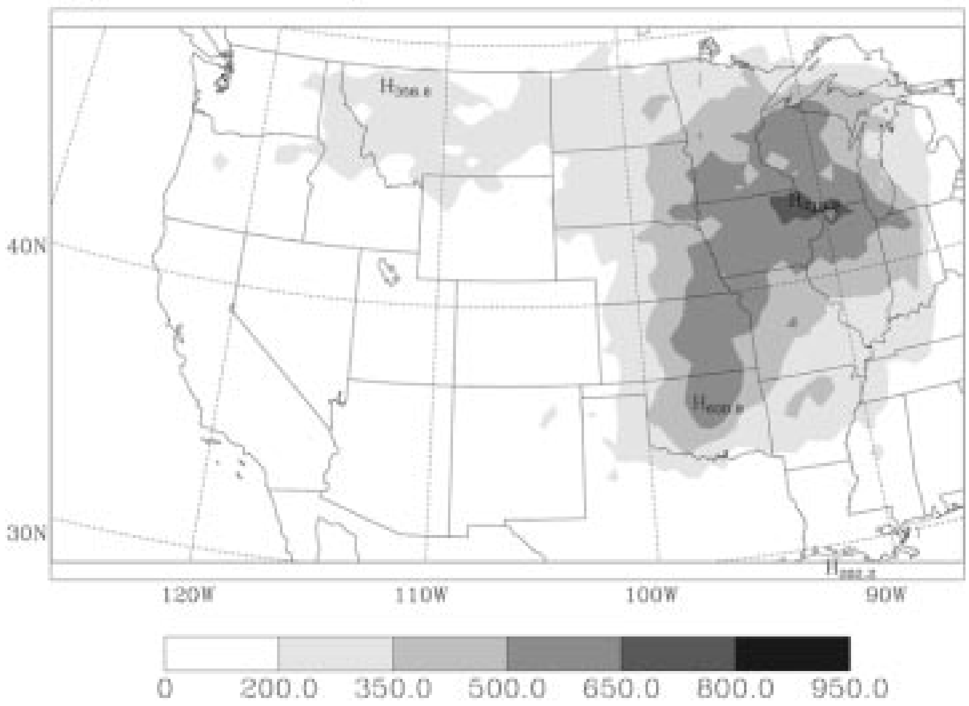


FIG. 4. Simulated MJJ rainfall totals (mm) for (a) SMDRY88 and (b) SMDRY93.

verted into rainwater. Rainwater is immediately precipitated out. The cloud properties provided by this scheme (cloud water and fractional cover) are used for cloud-radiation computations.

For convective precipitation, the scheme developed by Grell (1993) and described in detail by Grell et al. (1994) is employed. This scheme incorporates a simple cloud model wherein clouds are defined as two steady-state circulations consisting of an updraft and a downdraft. Mixing between the cloud and its environment

TABLE 4. RegCM simulations performed with the large domain (100 × 66 grid points, centered at 38′N, 100°W, 60-km resolution) and ECMWF boundary conditions for this study. SMF is the initial column soil moisture fraction.

Experiment	SMF	Period
LGWET88	~0.8	1 April–31 July 1988
LGDRY88	0.02	1 April–31 July 1988
LGWET93	~0.8	1 April–31 July 1993
LGDRY93	0.02	1 April–31 July 1993
LGFIX93	0.02	1 April–31 July 1993

TABLE 5. Results from RegCM simulations performed with the large domain. MJJ average daily precipitation and evaporation rates computed for the defined region UMB. Observed precipitation is derived from NCDC monthly mean station data. Observed evaporation is estimated by Trenberth and Guillemot (1996).

	P (mm day^{-1})	E (mm day^{-1})
OBSERVED 88	1.84	2.50
LGWET88	2.31	4.01
LGDRY88	1.55	1.86
OBSERVED93	5.62	4.00
LGWET93	4.52	3.85
LGDRY93	3.90	3.25
LGFIX93	3.57	2.67

occurs through entrainment/detrainment at the cloud base or cloud top. The mass fluxes in the updraft and downdraft are constant with height and the originating levels of the drafts are given by maximum and minimum ambient moist static energy. The scheme is activated when a parcel lifted from the updraft originating level eventually attains moist convection, and rainfall depends on an efficiency parameter that measures the fraction of the updraft condensate that re-evaporates in the downdraft. The scheme employs a stability-based closure similar to that adopted by Arakawa and Schubert (1974), which states that cumulus clouds stabilize the environment as fast as the large-scale and surface fluxes destabilize it.

The RegCM requires initialization of model prognostic variables (u, v, T, q, p_s, and T_s) at each horizontal model grid point and, excluding surface pressure (p_s) and surface temperature (T_s), at each model level. In addition, because the domain is of a limited area (not global), the lateral boundaries of the domain require time-dependent forcing of the model prognostic variables by applied external conditions. The external conditions are prescribed using global analyses from the ECMWF, as processed by Trenberth (1992), and interpolated to the model grid at 6-h intervals. A weighting function equal to one at the boundaries decreases exponentially inward. The buffer region is 12 grid points in the large domain experiments and 11 points in the small domain. The horizontal weighting function is given by $\text{func}(x) = \exp[-(x - 2)/\text{anudge}(k)]$, where x is the number of grid points from the boundary, and anudge(k) is the nudge factor at each vertical level (the strongest being at the top of the model atmosphere). For both large and small domains anudge varies between values of 3 (at the model top) and 1 (at the surface).

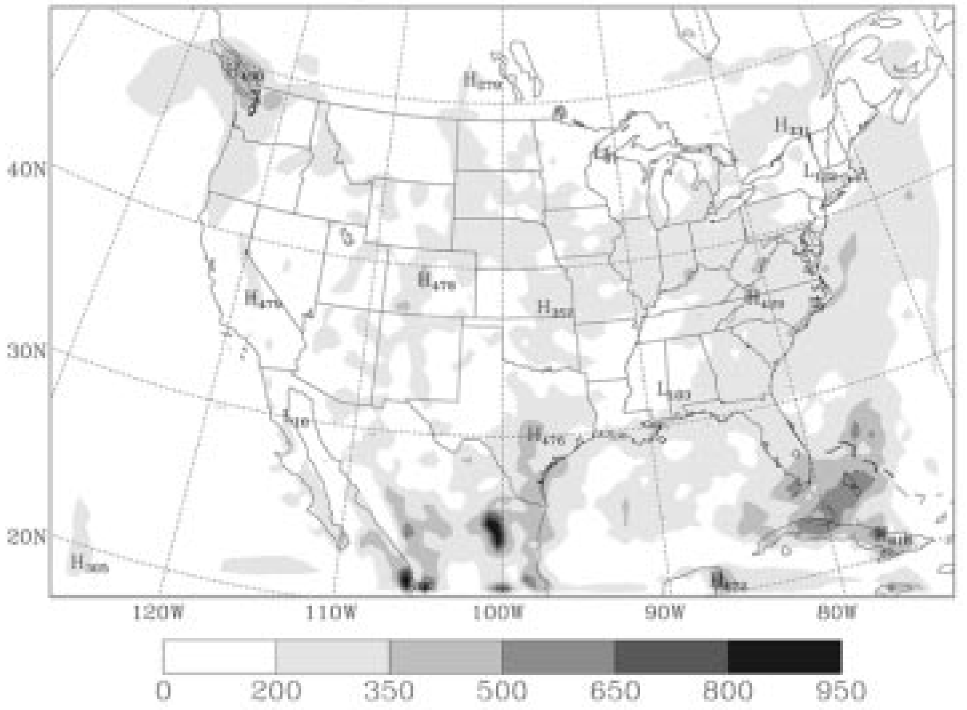
4. Large domain experiments

Five additional simulations are performed that are different from the small domain experiments in three ways. First, the domain is significantly larger. With 66 times 100 grid points it includes the eastern Pacific, western Atlantic, the Gulf of Mexico as far south as the Yucatan Peninsula, and the southern part of Canada (see Fig. 9 in section 5). Second, these simulations are initialized on 1 April, which is three weeks earlier than the small domain experiments. The effect of this difference will be discussed with the results. Third, the model resolution is 60 km in these large domain experiments, compared to 50 km used in the small domain runs. Test simulations have shown that resolution has a negligible effect on the model precipitation results between the range of 40 and 60 km. Thus, the resolution difference between small and large domain simulations is not considered important.

The five experiments are each four months duration (1 April–31 July) with lateral boundary forcing from ECMWF analyses. Similar to the small domain simulations, the large domain simulations are referred to as LGWET93, LGDRY93, LGWET88, and LGDRY88. Again, the wet simulations are initialized with a soil moisture fraction of approximately 0.8 and the dry simulations are initialized with a soil moisture fraction just above the wilting point (0.02) of the vegetation. One final simulation is completed for 1993 only, wherein the soil moisture is initialized as in LGDRY93 and fixed for the four months; that is, there is no feedback between precipitation and the soil moisture calculation, and thus the soil remains dry. This simulation is referred to as LGFIX93. Table 4 outlines the large domain simulations.

Results from these five large domain simulations are provided in Table 5. Compared with the observed MJJ precipitation, the LGWET88 and LGWET93 runs reasonably represent precipitation patterns for the two years (Fig. 5), although the area where precipitation is greater than 200 mm is larger than observed in 1988 and the area where precipitation is greater than 350 mm is smaller than observed in 1993. The tabulated results for the UMB show overprediction of precipitation in 1988 (2.31 simulated vs 1.84 mm day^{-1} observed) and underprediction in 1993 (4.52 simulated vs 5.62 mm day^{-1} observed). With these results, comparison of the large domain and small domain precipitation indicates that the small domain experiments better simulate the flood and drought conditions over the UMB. This is consistent with the stronger lateral forcing exerted by the analyses of observations in the small domain. Jones et al. (1995) showed that when using the larger domain, increasing divergence is found between the model solution and the

(a) WET88 MJJ Precipitation



(b) WET93 MJJ Precipitation

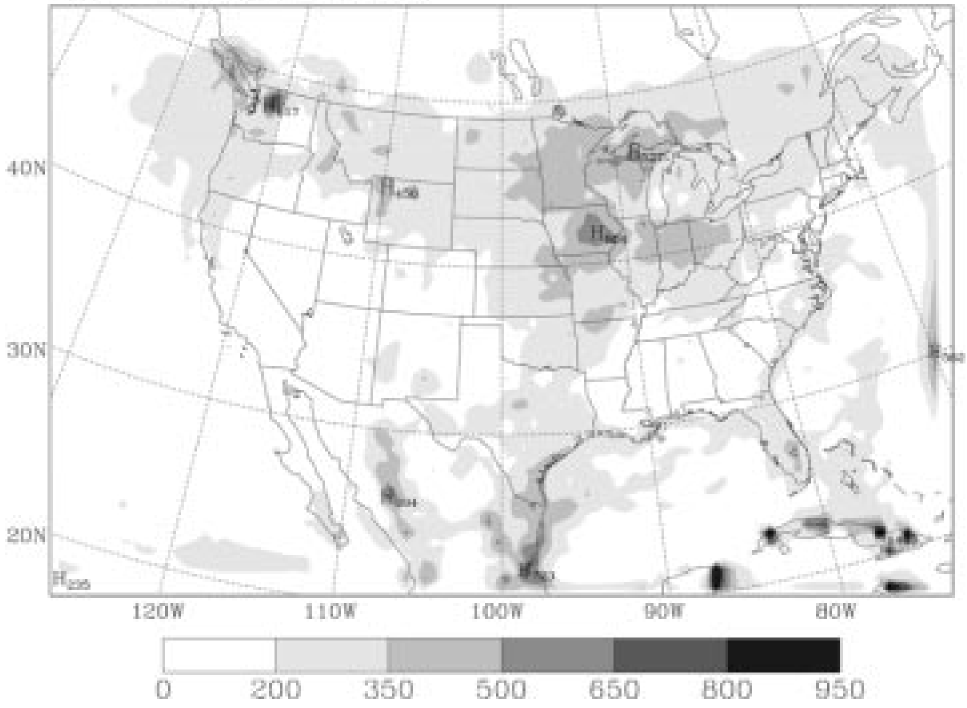


FIG. 5. Simulated MJJ rainfall totals (mm) for (a) LGWET88 and (b) LGWET93.

large-scale analyses. For the present experiment this effect results in a degradation of the simulation of the extreme events of 1988 and 1993.

Note that some aspects of the simulated precipitation patterns are significantly changed between the small and large domain runs, particularly in 1988. For example, the large maxima over Texas and Oklahoma seen in the small domain run is no longer present in the large domain run. These maxima were evidently due to spurious lateral boundary effects. Therefore, although the simulated precipitation amounts over the UMB region are somewhat degraded in the large domain runs, the simulation of spatial patterns is actually improved.

Precipitation maps from the LGDRY88 and LGDRY93 experiments are provided in Fig. 6. In these dry runs the precipitation is clearly reduced compared to the runs initialized wet (Fig. 5) for both years. The sensitivity is greater than in the small domain experiments and the feedback is clearly positive, with an increase of 14% in 1993 and 33% in 1988 for the UMB region. These large domain sensitivity results are in contrast to those obtained with the small domain, which showed little sensitivity to soil moisture. The possible causes for the different sensitivity are the domain specification, the initialization (start date), and the resolution. Model tests (not presented here) have shown the resolution effects between 50 and 60 km are not important in our results. The initialization date, which is 1 April in the large domain experiments and 22 April in the small domain, does have an effect. In the dry cases the soil moisture is specified at the start of the run, but precipitation is allowed to recharge the column. The large domain simulation has 21 additional days toward refilling the soil reservoir. In April 1993 the rainfall is substantial. The month-to-month evolution of precipitation difference in the LGWET93 and LGDRY93 simulations shows that, indeed, the largest sensitivity is in April (21%) and May (20%), and it decreases in June and July to 11%. Therefore, it is reasonable to expect that the sensitivity in the large domain would be smaller than that seen in the small domain based on the differences in start dates alone. But the sensitivity to initial soil moisture is smaller in the SMWET93 and SMDRY93. The only other possible cause for the sensitivity difference is the specification of domain. Evidently, the same model produces quite different sensitivities based on domain size.

Also notable is that the dominant forcing is large scale; even with dry initial conditions there is a factor of 2 change in UMB precipitation amounts between 1988 and 1993.

In the experiments of P96 the prescribed evaporation rates were held constant for the duration of the simulation. To test the dynamical mechanism offered by P96, that the moisture supply from the Gulf is enhanced by a drier surface and can compensate for reduced evaporation, we performed the LGFIX93 simulation, which is described in Table 4.

Table 5 shows that the precipitation is further decreased (21%) when the soil moisture is fixed for the duration of the simulation, and the evaporation rate remains low (note that in this experiment water intercepted by vegetation is still allowed to evaporate). Thus the dynamical mechanism offered by P96 and G96 does not appear to be functioning in these large domain results.

5. Analysis and discussion

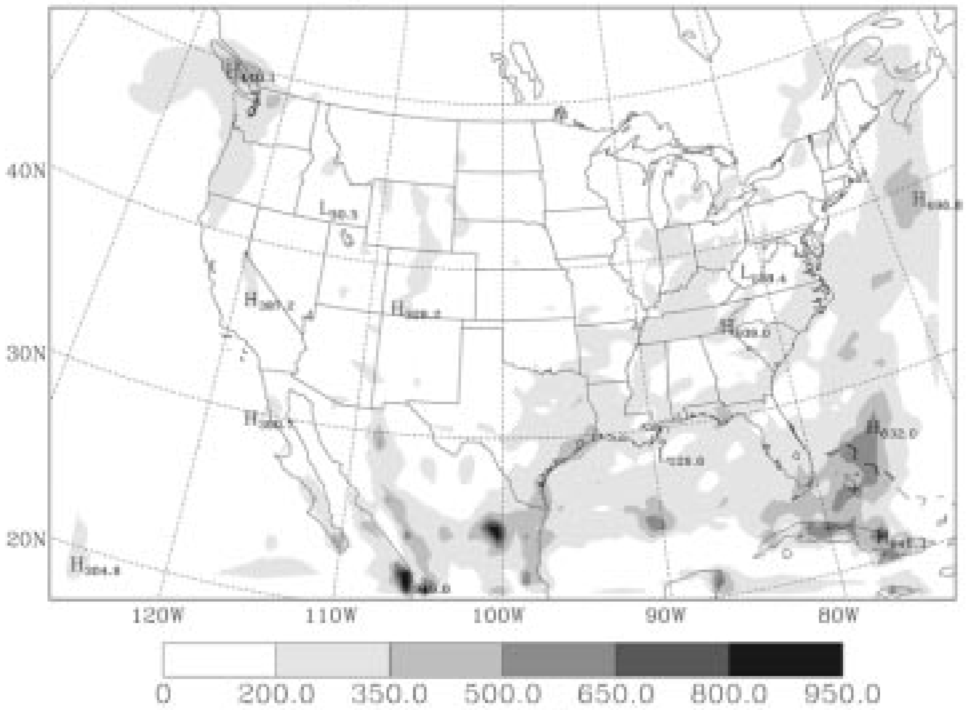
The results of the large domain simulations demonstrate a positive soil moisture feedback of approximately 14%–33%. These results are in general agreement with the global model results of B96, and they disagree substantially with the regional model results of P96. Still more surprising is the difference between the large and small domain results, which employ the same model.

Recall that the mechanisms defined by P96 and G96 (Fig. 2) both rely on enhanced moisture transport from the Gulf of Mexico due to a stronger LLJ over the drier surface. In addition B96 did not report an enhanced LLJ in their sensitivity studies with the global model. To investigate this, the LLJ and its effect on the meridional moisture transport are further analyzed in the small and large domain simulations. Figure 7 shows the MJJ mean meridional wind component from analyses (Fig. 7a) and from the small (Figs. 7b, c) and large (Figs. 7d, e) domain simulations for 1993. The plots in Fig. 7 show vertical cross sections (taken at a latitude of approximately 35° under the jet core) for the full west–east extent (in km) of the small and large domains. The analyses are shown for the small domain. Note that the small and large domain cross sections are presented with different horizontal scales. The observed LLJ is approximately twice as strong in 1993 as in 1988 (the 1988 result is not shown). This is in agreement with NCEP (National Center for Environmental Prediction) analyses (K. Mo 1997, personal communication). As the SMWET93 and LGWET93 simulations have been initialized with more realistic soil moisture values, we compare these simulations (Figs. 7b and d) with the analyses (Fig. 7a). In these wet simulations the strength of the LLJ and its vertical structure over the southern central plains appear to be better represented in the small domain simulations, where the boundary forcing from analyses has more influence. However, comparing the wet to the dry runs for each case, Figs. 7b to 7c and 7d to 7e, we find that the jet is significantly enhanced in the small domain simulations when initialized dry, whereas there is only a small enhancement of the jet in the large domain simulations. The meridional moisture transport (Fig. 8 shows SMWET93 and LGWET93 results for MJJ) is also significantly enhanced in the small domain solutions, whereas it is minimally affected in the large domain solutions. The small domain result is indeed similar to the effect seen in P96. Maps produced for 1988 demonstrate an even stronger enhancement (not shown here) of northward moisture transport by the LLJ.

It appears that the large and small domain simulations have very different dynamical responses to the surface forcing. A mechanism for this difference is proposed as follows.

The approximate domains are depicted in Fig. 9. The domain employed in the present study is large (3960 km × 6000 km), with boundaries a large distance from

(a) DRY88 MJJ Precipitation



(b) DRY93 MJJ Precipitation

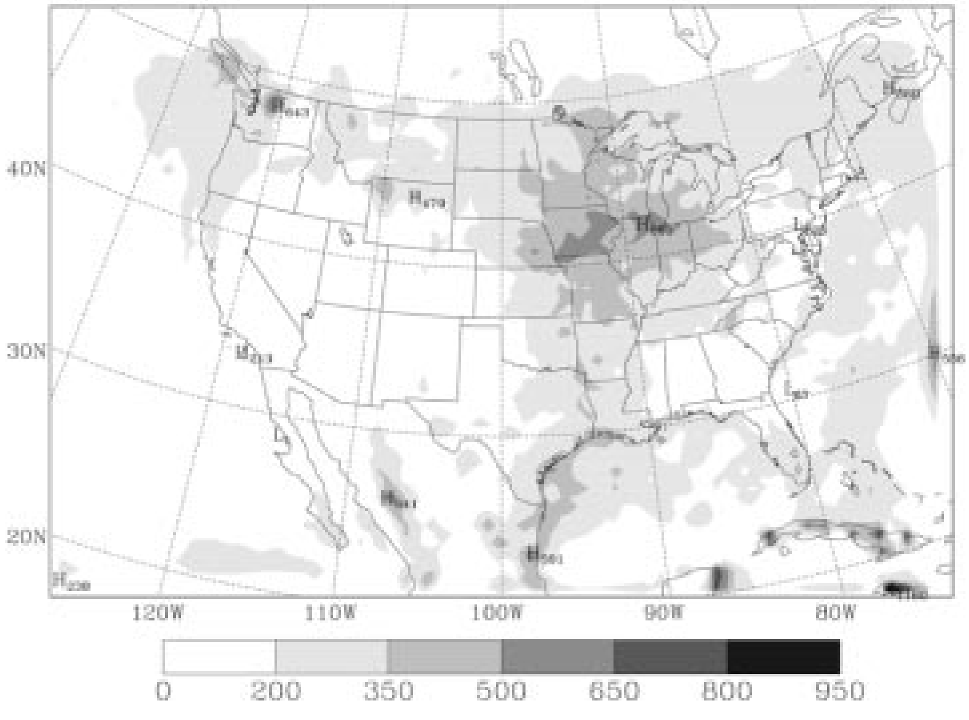


FIG. 6. Simulated MJJ rainfall totals (mm) for (a) LGDRY88 and (b) LGDRY93.

the central United States on all sides. P96 and G96 employ domains (labeled #1 and #2, respectively) of similar size and both have boundaries in the southeastern United States so that their lateral buffer areas are near the Mississippi basin region. Surface pressure is effectively constrained in the buffer regions of the limited-area domains by the lateral boundary forcing from analyses. In the small domain runs initialized with dry

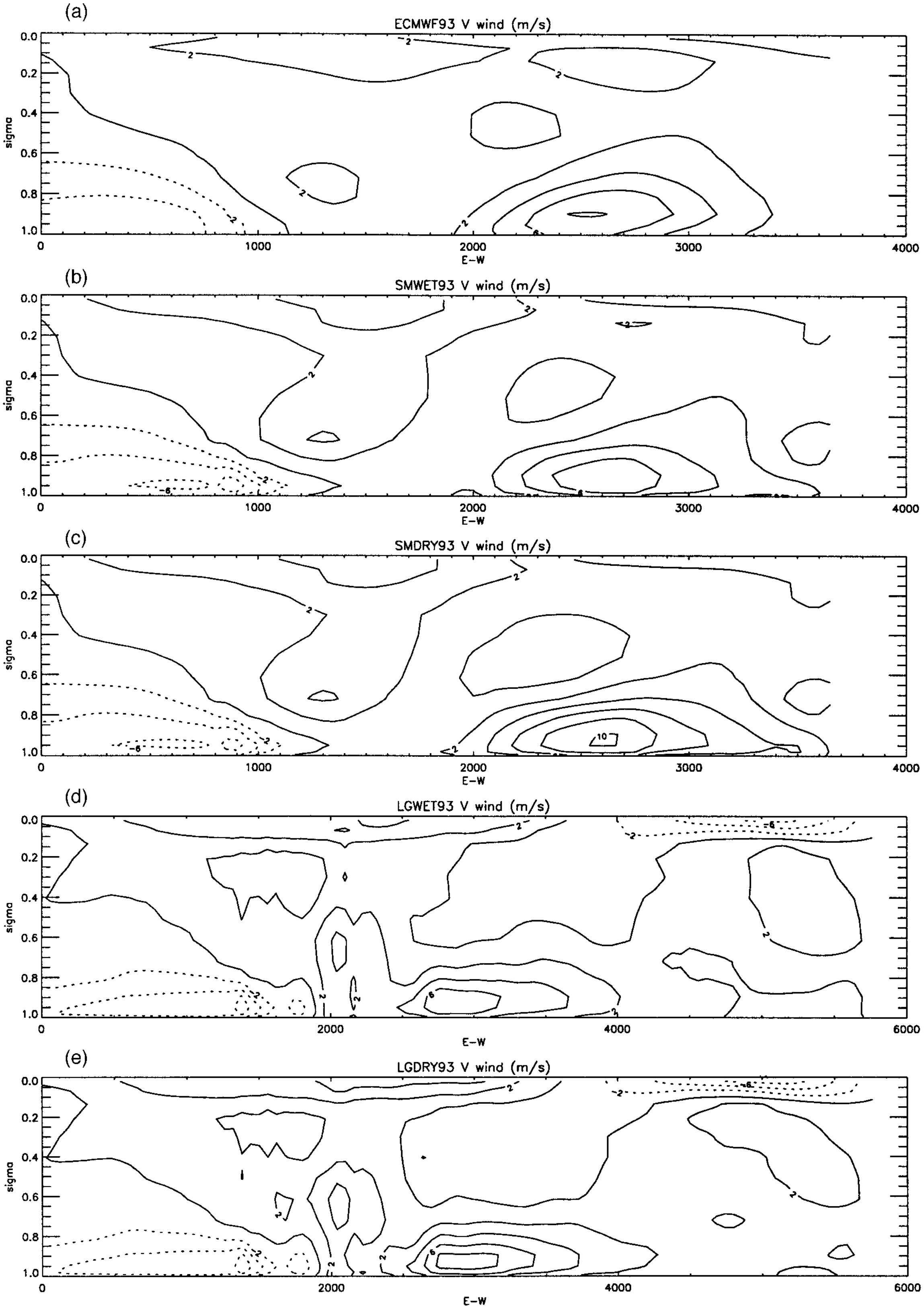


FIG. 7. Vertical by west–east cross sections showing MJJ mean meridional wind (m s^{-1}) for (a) ECMWF93, (b) SMWET93, (c) SMDRY93, (d) LGWET93, and (e) LGDRY93. Here N.B., the west–east extent is given in km and is greater for the large domain than the small domain. The cross sections are taken at approximately 35° lat under the jet core.

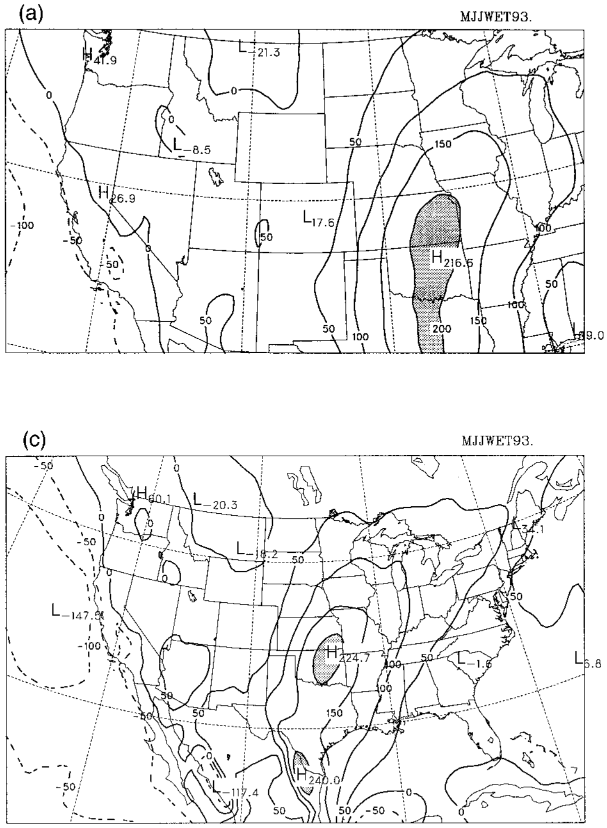


FIG. 8. MJJ vertically integrated northward moisture flux (kg m^{-1} s^{-1}) for (a) SMWET93, (b) SMDRY93, (c) LGWET93, and (d) LGDRY93.

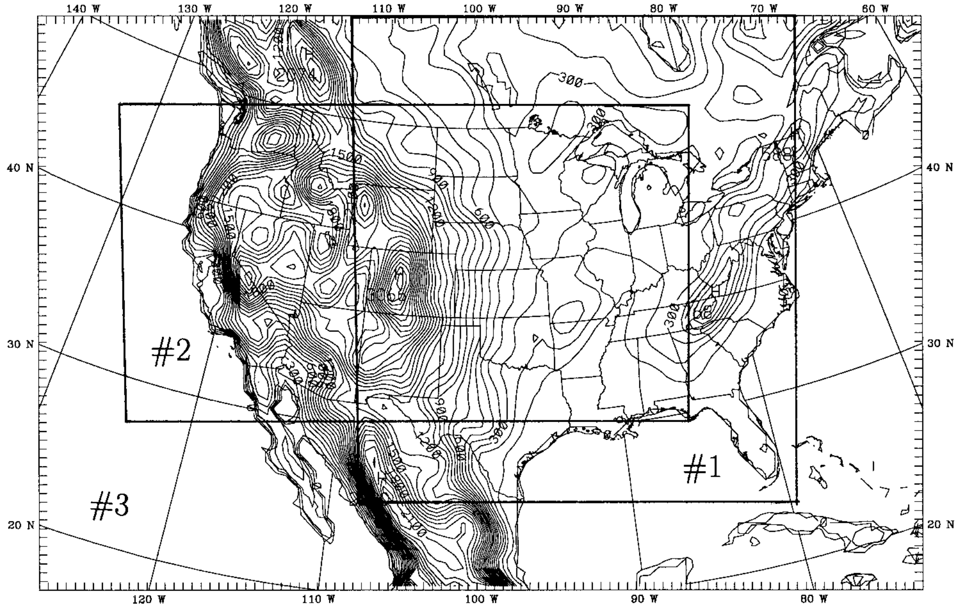


FIG. 9. Depiction of the domains employed by P96 (#1), G96 (#2), and the present study (#3), including buffer regions. Contours represent terrain height (m) employed in the present study.

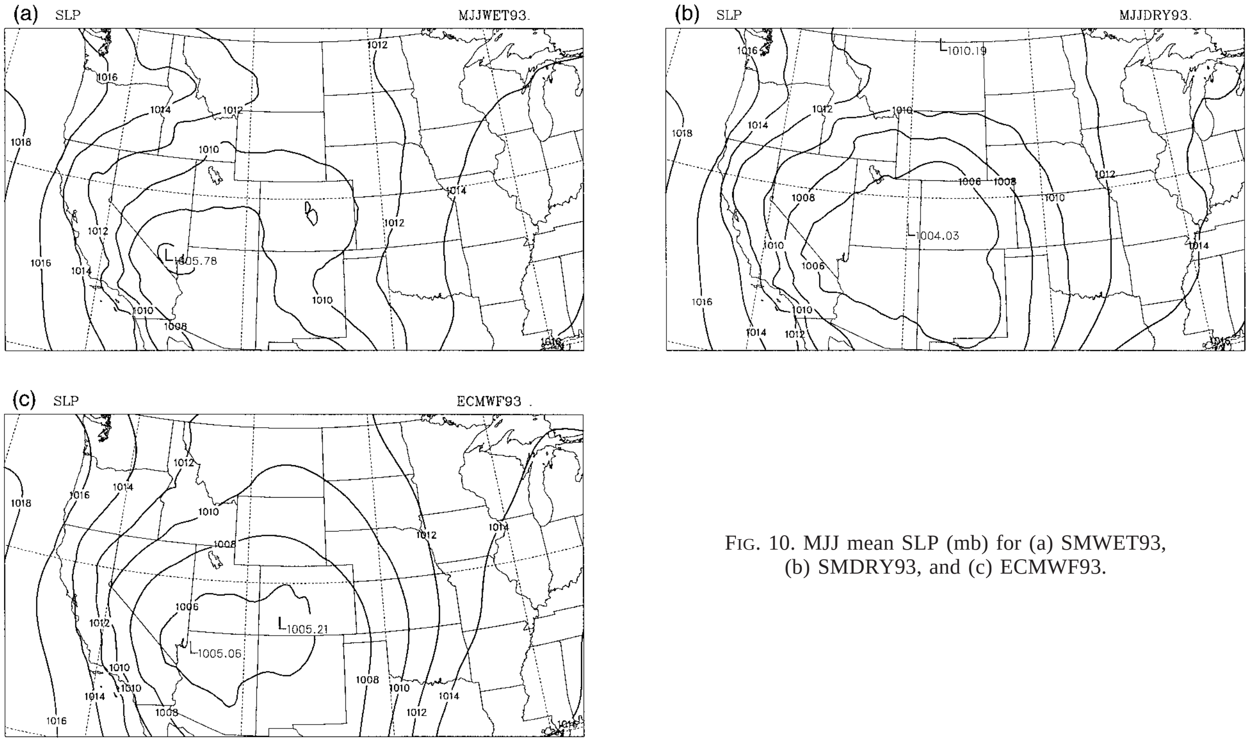


FIG. 10. MJJ mean SLP (mb) for (a) SMWET93, (b) SMDRY93, and (c) ECMWF93.

soil, the increased surface sensible heat flux causes upward motions in the lower to midtroposphere and divergence aloft, which result in reduced surface pressure over the central United States and generate an artificially enhanced pressure gradient between the interior of the domain and the lateral boundary regions where surface pressures are constrained. The increased pressure gradient enhances the LLJ, which transports more moisture in to the Mississippi basin. In the large domain solution this effect is not significant because there is less constraint by the boundaries. In Fig. 10 the 1993 MJJ mean sea level pressure (SLP) is given for the small domain (SMWET93 and SMDRY93) runs and analysis. While the wet run represents the analysis reasonably well, in the dry run the low pressure centered over the western United States is enhanced and, relative to the fixed SLP at the boundaries, creates a tighter west–east pressure gradient. This is a case where the local forcing feeds back to the large-scale circulation, but the small domain will not permit the feedback to occur. The imbalance between the internally generated circulation and the conditions imposed at the boundaries is reconciled by damping terms in the buffer region of the domain. Thus the enhanced LLJ in the G96 sensitivity simulations appears to be artificially generated by the proximity of the boundary region in their relatively small domain.

We suggest that in the simulations of P96 a similar effect is possible, although their results are likely to also depend on the convection and boundary layer schemes employed by the Utah LAM.

6. Implications and conclusions

The small and large domain results with RegCM demonstrate that simulated precipitation and moisture transport are affected by the choice of limited-area domain. The small domain UMB precipitation results are closer to observed than those from the large domain, since the boundaries of a smaller domain constrain the interior solution more toward the driving fields (which are derived from observations). This is in agreement with the results of Jones et al. (1995). This is also in agreement with Jones et al. (1997), where a substantial divergence is found between the regional model solution and driving GCM solution in equilibrium-doubled CO_2 simulations using a large domain.

The size of the domain and location of boundaries also significantly affects the sensitivity of the simulated fields to soil moisture. The simulation of sensitivity computed in the large domain experiments is believed to be more realistic. The implications of this result are important. In sensitivity studies of physical processes that occur in a limited-area model domain interior, the boundaries must be placed well outside the region of influence of the process being studied. Estimates for such a region of influence must be made for the individual application of the regional climate model, with the criterion that the boundaries must be far enough away from the internal processes so as not to interfere with the response of the model solution to the relevant forcings being modified.

Thus limited-area domain size and location of boundaries must be carefully considered when performing regional climate model simulations, particularly when testing the sensitivity to physical processes internal to the domain.

Our analysis supports the conclusion that the precipitation response to soil moisture in the central United States is positive in both 1988 and 1993. The large domain results show a 14%–33% increase in precipitation, whereas the ECMWF model results were approximately 50%. The 14% difference seen in the 1993 experiments is a conservative result due to the 1 April start date and soil moisture recharge, which occurs in the LGDRY93 simulation. In addition, differences in physical parameterizations and simulation periods between the present study and B96 might account for the smaller sensitivity seen in the RegCM as compared to the global model. The soil moisture feedback results reported by G96 and P96 are believed to be affected by artificially enhanced pressure gradients, resulting from the proximity of lateral boundaries to the inflow region of the LLJ.

Our study emphasizes the different effects that domain size and lateral boundary conditions might have on model *simulations* and model *sensitivity* to internal processes. Given good quality observed large-scale forcing fields, relatively small domains, in which a tight lateral forcing prevails, are likely to give better overall simulations. However, as we have shown, the lateral forcing may produce spurious dynamical effects when sensitivity to internal model processes is tested. In this case, larger domains, in which the model solution is more free to respond to variations in internal parameters, is likely to be preferable. Overall, our results indicate that careful consideration of domain choice and location of boundaries should be given when applying limited-area models.

Acknowledgments. The authors thank Robert Dickinson for useful discussions regarding this work, and two anonymous reviewers for their constructive comments. Supercomputing resources for this work were provided by NCAR. This research was funded in part by Inter-Agency Agreement W-18 077 NASA/NSF.

REFERENCES

Anthes, R. A., Y. H. Kuo, E. Y. Hsie, S. Low-Nam, and T. W. Bettge, 1989: Estimation of episodic and climatological skill and uncertainty in regional numerical models. *Quart. J. Roy. Meteor. Soc.,* **115,** 763–806.

Arakawa, A., and W. H. Shubert, 1974: Interaction of a cumulus cloud ensemble with the large scale environment, Part I. *J. Atmos. Sci.,* **31,** 674–701.

Beljaars, A. C. M., P. Viterbo, M. J. Miller, and A. K. Betts, 1996: The anomalous rainfall over the United States during July 1993: Sensitivity to land surface parameterization and soil moisture anomalies. *Mon. Wea. Rev.,* **124,** 362–383.

Cullen, M. J. P., 1993: The unified forecast/climate model. *Meteor. Mag.,* **122,** 81–94.

Dickinson, R. E., R. M. Errico, F. Giorgi, and G. T. Bates, 1989: A regional climate model for the western United States. *Climate Change,* **15,** 383–422.

——, A. Henderson-Sellers, and P. Kennedy, 1993: Biosphere–Atmosphere Transfer Scheme (BATS) version 1e as coupled to the NCAR Community Climate Model. NCAR Tech. Note NCAR/TN-387+STR, 72 pp. [Available from the National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.]

Giorgi, F., 1990: Simulation of regional climate using a limited area model nested in a general circulation model. *J. Climate,* **3,** 941–963.

——, and M. R. Marinucci, 1996: A study of the sensitivity of simulated precipitation to model resolution and its implications for climate studies. *Mon. Wea. Rev.,* **124,** 148–166.

——, ——, and G. T. Bates, 1993a: Development of a second-generation regional climate model (ReGCM2). Part I: Boundary layer and radiative transfer processes. *Mon. Wea. Rev.,* **121,** 2795–2813.

——, ——, and ——, 1993b: Development of a second-generation regional climate model (ReGCM2). Part II: Convective processes and assimilation of lateral boundary conditions. *Mon. Wea. Rev.,* **121,** 2814–2832.

——, L. O. Mearns, C. Shields, and L. Mayer, 1996: A regional model study of the importance of local versus remote controls of the 1988 drought and the 1993 flood over the central United States. *J. Climate,* **9,** 1150–1162.

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.,* **121,** 764–787.

——, J. Dudhia, and D. R. Stauffer, 1994: A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 121 pp. [Available from National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.]

Holtslag, A. A. M., and B. A. Boville, 1993: Local versus nonlocal boundary layer diffusion in a global climate model. *J. Climate,* **6,** 1825–1842.

——, E. I. F. de Bruijn, and H. L. Pan, 1990: A high resolution air mass transformation model for short-range weather forecasting. *Mon. Wea. Rev.,* **118,** 1561–1575.

Hsie, E. Y., R. A. Anthes, and D. Keyser, 1984: Numerical simulation of frontogenesis in a moist atmosphere. *J. Atmos. Sci.,* **41,** 2581–2594.

Jones, R. G., J. M. Murphy, and M. Noguer, 1995: Simulation of climate change over Europe using a nested regional-climate model. Part I: Assessment of control climate, including sensitivity to location of lateral boundaries. *Quart. J. Roy. Meteor. Soc.,* **121,** 1413–1449.

——, ——, ——, and A. B. Keen, 1997: Simulation of climate change over Europe using a nested regional climate model. Part II: Comparison of driving and regional model responses to a doubling of carbon dioxide. *Quart. J. Roy. Meteor. Soc.,* **123,** 265–292.

Paegle, J., K. C. Mo, and J. Nogués-Paegle, 1996: Dependence of simulated precipitation on surface evaporation during the 1993 United States summer floods. *Mon. Wea. Rev.,* **124,** 345–361.

Reynolds, R. W., 1988: A real time global sea surface tempeature analysis. *J. Climate,* **1,** 75–86.

Trenberth, K. E., 1992: Global analyses from ECMWF. NCAR Tech. Note NCAR/TN-373+STR, 191 pp.

——, and C. J. Guillemot, 1996: Physical processes involved in the 1988 drought and 1993 floods in North America. *J. Climate,* **9,** 1288–1298.