P2.9 ROLE OF MESOSCALE PROCESSES IN CLIMATE CHANGE OVER THE CENTRAL UNITED STATES – A WARMING "HOLE"

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1. INTRODUCTION

A significant dynamical feature that regulates moisture flow in the central US, and hence summertime precipitation, is the Great Plains nocturnal low-level jet (LLJ). The LLJ is created by a combination of large-scale orography (slope from the Rocky Mountains to the Mississippi River Valley), diurnal variations in surface heating, and synoptic dynamics (e.g., Fast and McCorcle, 1990). Convergence near the northern terminus of the LLJ aids in release of conditional instability and organization of convection into coherent mesoscale convective systems (MCSs) (Augustine and Caracena, 1994). These MCSs produce copious amounts of rainfall. These summertime heavy rainfall events recharge moisture-depleted soils that are deep and rich in organic matter and thus can represent a substantial reservoir of water for transpiration by plants. A change in climate that affects this moisture reservoir likely will trigger soil-moisture feedbacks to the mesoscale atmospheric processes.

The key to accurate simulation of atmospheric processes in the central U.S. is accurate simulation of precipitation that links atmospheric and hydrological processes. Summer precipitation in the central US has a nocturnal maximum, a unique feature that is associated with the LLJ and MCS. The horizontal resolution of current global models (GCMs) is too coarse to simulate these mesoscale features. We have used results from a GCM as lateral boundary conditions for a regional climate model in order to produce enhanced-resolution climate change simulations for the US. Use of enhanced resolution may permit better representation of the linkage between the LLJ, MCSs, and regional precipitation.

2. REGIONAL MODEL AND CLIMATE SCENARIOS

We used RegCM2 (Giorgi et al., 1993a, b), which incorporates the BATS version 1e (Dickinson et al. 1992) surface package and the modified Grell scheme (Grell 1993), a simplified version of Arakawa-Schubert convection scheme. Large-scale precipitation was computed using a simple warm-cloud-physics, explicit-moisture scheme. The BATS land surface scheme in RegCM2 has 18 categories of land use and 12 soil types with three overlying soil layers: top layer, root zone and deep layer. The depth of the top layer is fixed at 10 cm while the root zone depth varies depending on land use type. RegCM2 was configured with 101x75 grid points centered at (100°W, 37.5°N) with a horizontal grid spacing of 52 km. The resulting domain covers the continental U.S., parts of Canada and Mexico, and neighboring oceans.

A transient greenhouse gas (GHG) simulation by the Hadley Centre GCM Version 2 (HadCM2; Johns et al., 1997) provided boundary conditions, including SSTs, for simulations of control and scenario climates using RegCM2. The spatial resolution of HadCM2 is 2.5° (latitude) x 3.75° (longitude) with 19 vertical levels. Lateral boundary conditions obtained from HadCM2 were assimilated over a 15-grid wide forcing frame in RegCM2 (Pan et al. 2001). The HadCM2 transient GHG simulation assumed a 1% per year increase of effective greenhouse gases after 1990. The 10-year window selected for the present climate corresponds roughly to the 1990's, while the window used to represent future climate was the decade 2040-2049 in the transient simulation.

3. WARMING "HOLE"

We examined climate changes for daily maximum and minimum temperatures during all seasons. (In this study "climate change" refers to the difference in the 10-year means between 2040's, i.e., the scenario climate, and 1990's, i.e., current climate). The most notable feature in the change is a local minimum of warming in the central US projected by RegCM2. This feature was most prominent in summer (JJA) and was most easily seen in daily maximum air temperatures. The projected change in daily maximum temperature in summer has a well-defined minimum warming center in the Central US, resulting in a

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warming “hole”. The warming at the hole center is less than 0.5K, which is about 2.5K lower than the surrounding region (Fig. 1). The warming hole starts to develop in June, peaks in August, and gradually diminishes through September and October (Fig. 2). The daily maximum temperature change ($\Delta T_{\max}$) in August is 2.6K lower than the domain (land) average. The warming hole is less evident in other seasons and even reverses sign in December.

Most GCMs project substantial warming over the US in the future (e.g., Mearns et al. 2002). RegCM2 simulated general warming over the US with a warming hole in the middle of the continent. Is such a warming hole plausible? To answer this question we examined past observed temperature changes. The daily mean temperature over the US has increased during the past century (1901-2000), but $T_{\max}$ increased least in the central US. In fact, $T_{\max}$ decreased noticeably in the central US in the last quarter century (IPCC, 2001) (Fig. 3). The cooling is at approximately the same location as the warning hole simulated by RegCM2.

In addition, recent GCM simulations with increased horizontal resolution and refined physical parameterizations tend to project less warming in the central US. We surveyed the IPCC models (http://ipcc-ddc.cru.uea.ac.uk/). Out of five available GCMs in the data set, three models that report $T_{\max}$ and $T_{\min}$ changes separately showed local minimum warming in summer for the period around 1970's-2050's in the central US. The incorporation of sulfate aerosols forcing in the GCMs tends to promote the local minimum in warming. Thus the warming hole is not only possible in the future, but also is occurring already in the Central US.

The warming hole can be explained through analysis of changes in the hydrological cycle. Changes in mean upper-air (500 hPa) heights for summer predicted by RegCM2 indicate enhanced ridging over the western US and troughing from Lake Superior to the Texas panhandle. This is notable because climatological observations show that such an upper-air pattern is conducive to LLJ development (Uccellini and Johnson, 1979; Arritt et al., 1997), implying that the LLJ may be stronger or more frequent in the future climate. We analyzed wind fields in the lower troposphere using the LLJ criterion that defines a LLJ as an occurrence of maximum southerly wind speeds greater than 12 m s^{-1} below 3 km, decreasing by at least 6 m s^{-1} aloft (Bonner, 1968). In the current-climate simulation a relatively narrow swath of LLJ occurs with high frequency over Texas-Oklahoma extending into the north-central US, in agreement with the observed spatial distribution of LLJ occurrences. In the future-climate simulation the northward extent of the swath is diminished, but the LLJ occurs more frequently in the south, resulting in an LLJ occurrence increase to the south and decrease to the north of the warming hole (Fig. 4). The region of reduced warming coincides with the terminus region of the LLJ changes, which is a favorable location for development of mesoscale convective systems.

Increased southerly flow and moisture advection by the LLJ lead to increased cloud fraction over the hole region. This increase in cloudiness reduced solar radiation reaching the ground and thus inhibited surface warming. Increased convergence at the LLJ terminus also produced higher precipitation, particularly during May through July; additionally, reduced surface warming allowed for only marginally increased evaporation. The result is that while both precipitation (P) and evaporation (E) are higher in the future climate, the difference P-E is greater, so that soil moisture is increased (not shown).

We therefore construct the following scenario for changes in the hydrological cycle due to climate change in the central US. Under greenhouse-induced warming the LLJ intensifies and occurs with higher frequency south of its current location from May through July (Fig. 5a). Greater moisture transport by the LLJ enhances development of MCSs near the northern terminus of the LLJ, producing increased precipitation from May through July in the future climate (Fig. 5b). This enhanced precipitation leads to increased summertime soil moisture (Fig. 5c), prolonging the period of higher surface evapotranspiration and reduced soil surface temperatures into August and September (Fig. 5d). The net result is persistent cooler near-surface temperatures in the scenario climate. We emphasize the role of more fully-charged soil moisture reservoir in providing additional “climate memory". We note that this climate memory may be even greater in nature than in the model, because the land-surface parameterization in the model does not account for the high organic matter content of these soils (which increases their moisture-holding capacity).

4. SUMMARY AND DISCUSSION

We have used results from a global model as lateral boundary conditions for a regional climate model in order to produce enhanced-resolution climate change simulations for the US. Results showed a “hole” in the warming pattern for the central US. The hole was shown in agreement with past observed temperature trends in last century. In addition recent GCMs with improved horizontal resolution and refined physical parameterizations have projected a similar local minimum warming in the central US, though with smaller amplitude than our results (presumably due to GCM’s coarser horizontal resolution).

The fact that the warming hole occurred only over the central US can be traced back to local-scale feedbacks in the hydrological cycle. LLJ occurrence is projected to increase to the south-central US and decrease to north-central US. The increased moisture convergence in the central US in late spring/early summer triggers a sequences of mesoscale atmospheric and hydrological processes whose feedbacks maintain the warming hole in late summer.

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REFERENCES

Arritt, R.W. and D.C. Goering, 1999: Inference of effects of global climate change on mesoscale climate over the central U.S. *Eighth Conference on Mesoscale Processes*, American Meteorological Society, Boulder, Colorado.

Bonner, W.D., 1968: Climatology of the low-level jet. *Mon. Wea. Rev.*, **96**, 833-850.

Dickinson, R. E., A. Henderson-Sellers, and P. J. Kennedy, 1992: Biosphere-atmosphere transfer scheme (BATS) version 1e as coupled to NCAR community climate model, *NCAR Tech. Note 387+STR*, 72 pp. (Available from Natl. Cent. for Atmos. Res., Boulder, Colo.).

Fast, J. D., and M. D. McCorcle, 1990: A two-dimensional numerical sensitivity study of the Great Plains low-level jet. *Mon. Wea. Rev*., **118**, 151-163.

Giorgi, F., M. R. Marinucci, G. T. Bates, and G. De Canio, 1993a: Development of a second-generation regional climate model (RegCM2), I, Boundary-layer and radiative transfer, *Mon. Wea. Rev.,* **121**, 2794-2813.

Giorgi, F., M. R. Marinucci, G. T. Bates, and G. De Canio, 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.

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

IPCC, 2001: Climate Change 2002: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

Johns, T. C., R. E., Carnell, J. F., Crossley, J. M. Gregory, J. F. B. Mitchell, C. A. Senior, S. F. B. Tett, and R. A. Wood, 1997: The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup, and validation. *Climate Dyn*., **13**, 103-134.

Mearns, L.O, F. Giorgi, L. McDaniel, and C. Shields, 2002: Climate scenario for the southeastern U.S. based on GCM and regional model simulations, submitted to Climatic Change.

Pan, Z., J.H. Christensen, R.W. Arritt, W. J. Gutowski, Jr., E.S. Takle, and F. Otenio, 2001: Evaluation of uncertainties in regional climate change simulations. *J. Geophys Res., **106**, 17735-17751.*

Uccellini, L. W., and D. R. Johnson, 1979: The coupling of upper and lower tropospheric jet streaks and implications for the development of severe convective storms. *Mon. Wea. Rev*., **107**, 682-703.

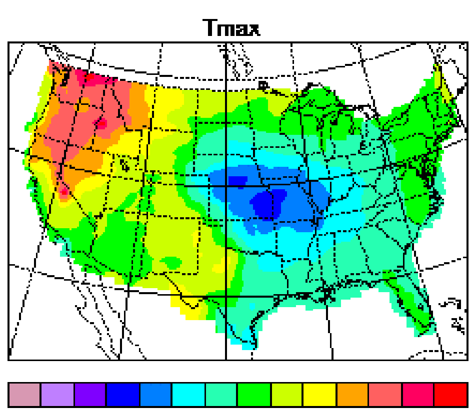

Fig. 1. Change (scenario decade of 2040's minus decade of 1990's) in daily maximum temperature (K).

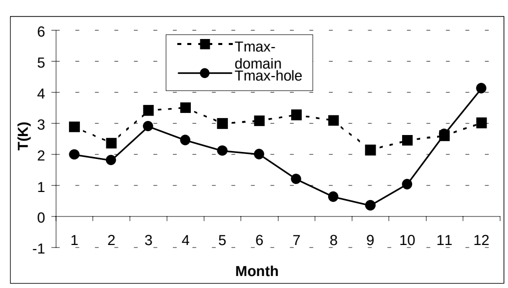

Fig. 2. Time series of monthly-mean daily maximum temperature averaged over the warming hole delineated by (99-92^{o}W,35-40^{o}N) latitude/longitude box and for the land portion of the entire domain.

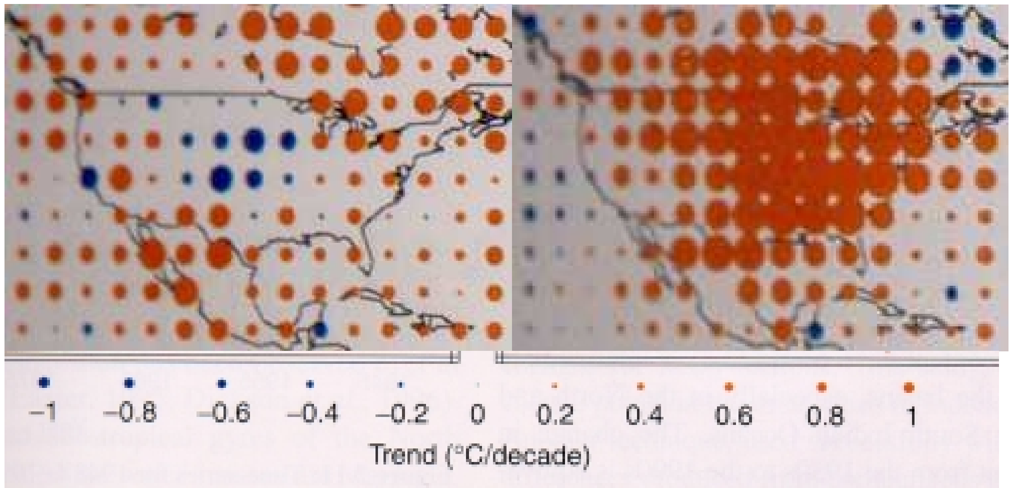

Fig. 3. Observed summer (JJA) daily maximum temperature changes during 1976-2000. (Adapted from IPCC, 2001). Note that dot sizes in the label are not drawn to scale.

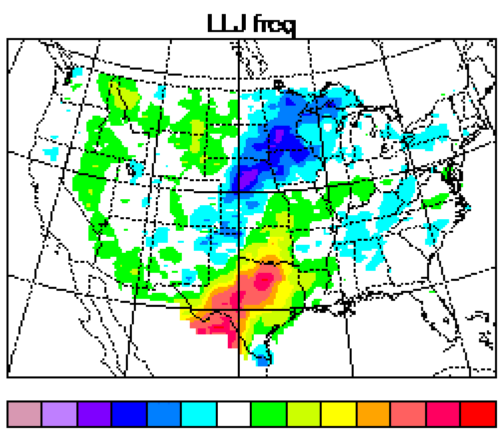

Fig. 4. Climate change (2040's-1990's) in low-level jet frequency (%) at 06 UTC in summer.

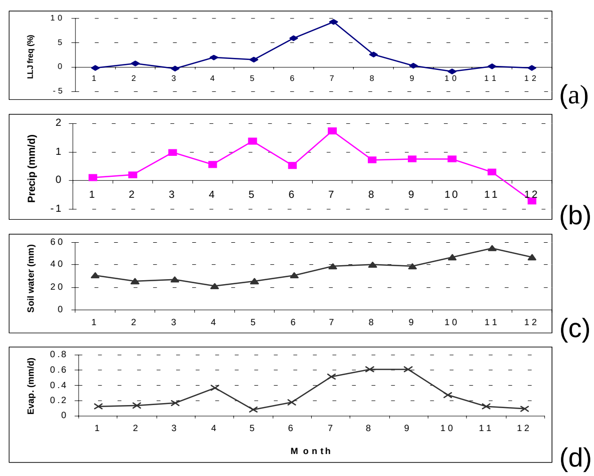

Fig. 5. Mean monthly change: (a) Low-level jet frequency, (b) precipitation, (c) soil water content in root zone, and (d) daily evapotranspiration. (a) is computed upstream of the hole and (b), (c) and (d) are evaluated in the hole.