The Role of the North American Topography on the Maintenance of the Great Plains Summer Low-Level Jet*

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ABSTRACT

Summer precipitation over the central United States depends strongly on the strength of the Great Plains low-level jet (LLJ). The Geophysical Fluid Dynamics Laboratory’s new generation of the atmospheric general circulation model (GCM) and the linear and nonlinear stationary wave models are used in this study to examine the role of North American topography in maintaining the Great Plains summer mean LLJ and precipitation. Atmospheric GCM experiments were first performed with and without the North American topography and with prescribed climatological sea surface temperatures. Results show that the Great Plains LLJ disappears completely in the experiment when the North American topography is removed, while the summer seasonal mean LLJ is well simulated in the experiment with full earth topography. In the absence of the North American topography, the summer precipitation is significantly reduced over the central United States and increased along the Gulf States and northeast Mexico.

Linear and nonlinear stationary wave models are used to determine the physical mechanisms through which the North American topography maintains the Great Plains time mean LLJ. Possible mechanisms include the physical blocking of the topography and the induced flow over and around the mountains, the thermal effect due to the elevation of the topography, and the transient thermal and vorticity forcing due to the modification of transient eddy activities in the presence of the topography. The linear and nonlinear model results indicate that the dominant mechanism for maintaining the time mean Great Plains LLJ is through the nonlinear effect of the trade wind along the southern flank of the North Atlantic subtropical high encountering the east slope of the Sierra Oriental and causing the flow to turn northward. As the flow turns north along the east slope of the North American topography, it obtains anticyclonic shear vorticity and thus the LLJ. The effect of the thermal forcing is negligible, while the effect of transient forcing is only important in extending the jet farther northward and eastward. The results suggest that variations in the strength of the North Atlantic subtropical anticyclone and the associated trade wind over the Caribbean Sea and the Gulf of Mexico may be important for understanding the interannual variation of the Great Plains LLJ and U.S. precipitation.

1. Introduction

It is widely recognized that the presence of an intense low-level jet (LLJ) over the Great Plains of the United States is essential for the moisture transport and precipitation over the central United States during summer (Means 1952; Benton and Estoque 1954; Pitchford and London 1962; Rasmussen 1967; Wallace 1975; Higgins et al. 1997; Min and Schubert 1997; Schubert et al. 1998; among others). The LLJ shows large diurnal variation, with peak strength in the late night and early morning hours. It does, however, show up as an intense jet in the summer time mean flow as well. Furthermore, the droughts and floods over the Great Plains depend strongly on the intensity of the time mean LLJ (Bell and Janowiak 1995; Mo et al. 1995; Arritt et al. 1997; Mo and Berbery 2004). Figures 1a and 1b illustrate the
Fig. 1. The 850-mb wind vectors and magnitude (shadings) for (a) AMJ 1988, (b) JJA 1993, (c) AMJ, and (d) JJA climatological mean from 1979–2003, (e) difference between AMJ 1988 and AMJ climate and (f) between JJA 1993 and JJA climate from NCEP–NCAR reanalysis II. Vector and shading scales are as shown, in m s$^{-1}$. 
850-mb wind vectors and strength (shadings) for April, May, and June (AMJ) 1988, and June, July, and August (JJA) 1993, respectively. The strong LLJ is clearly present in Fig. 1b for the 1993 summer, while it is only weakly present in Fig. 1a for early spring and late summer of 1988. Comparing to the climatological mean taken from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis II (Kanamitsu et al. 2002) for the period of 1979 and 2003 for AMJ (Fig. 1c) and JJA (Fig. 1d), one sees the much strengthened LLJ in 1993 and weakened jet in 1988, as is clearly shown in the anomalous wind vectors and magnitude (Figs. 1e,f).

Figure 1 indicates that the time mean LLJ is significantly (about 50%) enhanced during the major flood year for the Mississippi River valley, and reduced during the record drought year for the area. We choose AMJ for 1988 since the drought peaked in late spring and early summer.

The mechanisms proposed to account for the Great Plains LLJ have been mainly focused on the nocturnal nature of the jet. Stensrud (1996) provides a comprehensive review of the LLJ and its proposed mechanisms. The most popular theory is the so-called inertial oscillation mechanism first proposed by Blackadar (1957). It relies on the fact that during the daytime, the frictional stress at the surface is felt throughout the boundary layer due to strong mixing, while during the night, the radiative cooling at the surface stabilizes the boundary layer and thus reduces dramatically the frictional stress. The reduction leads to a supergeostrophic flow that needs to adjust to the existing pressure gradient force. This adjustment then triggers the inertial oscillation and the boundary layer jet development. This mechanism can exist anywhere there is a well-defined boundary layer, not just over the Great Plains. The preference for the location of the Great Plains LLJ leads to the theory proposed first by Holton (1967) who suggested the diurnal oscillations due to the heating and cooling of sloping terrain could be responsible for the strength and persistence of the LLJ. However, the phase of the geostrophic wind oscillation due to the diurnal variation of the sloping terrain thermal forcing does not match that for the LLJ. Bonner and Paegle (1970) demonstrated that joint consideration of a time-varying geostrophic wind and a time-varying frictional stress could produce strong wind maxima at approximately the times indicated by observations.

Another theory to account for the existence of the Great Plains LLJ that is geographically specific is proposed by Wexler (1961), who suggested that the LLJ is similar in mechanism to the western boundary currents in the ocean. Because of the physical blocking of the North American Cordillera, the westward-flowing trade winds are forced to turn northward upon encountering the eastern slope of the Sierra Oriental, while the equatorial side of the trade wind flow continues westward to cross Central America to reach the eastern Pacific. From potential vorticity conservation, a northward flowing air column will have to gain anticyclonic vorticity in order to compensate for the increase of planetary vorticity. Thus an anticyclonic shear in the northward component of the wind must develop, thus creating a maximum northward flowing LLJ. The diurnal variation of the jet is explained through the decoupling of the surface friction at night due to the stable boundary layer that shields surface friction from the jet.

A theory independent of the boundary layer processes has been proposed as well, which involves the interaction between upper-tropospheric jet streaks and leeside cyclogenesis in the development of the LLJ in the Great Plains (Uccellini and Johnson 1979; Uccellini 1980). A similar mechanism is proposed by Byerle and Paegle (2003) to understand the interannual variability of the Great Plains LLJ. Mo and Berbery (2004) further examined such a mechanism and its possible link to the negative relation between Great Plains summer precipitation and the North American monsoon rainfall. Additionally, Rodwell and Hoskins (2001) examined the maintenance of the subtropical anticyclones and considered the Great Plains LLJ as an extension of the North Atlantic subtropical high over the North American landmass. They emphasize the collective effects of the topography and the monsoonal heating in the maintenance of the subtropical anticyclones. In a recent study (Pan et al. 2004), the role of the North American topography on the LLJ is explicitly examined using a regional climate model and the 1993 flood case. The study shows a significant fluctuation of the Great Plains LLJ when the topography is flattened. It is not entirely clear whether the thermal or mechanical forcing of the North American Cordillera is more important in the generation and maintenance of the time mean Great Plains LLJ as shown in Fig. 1d. It is also not clear whether the LLJ is mainly forced by the topographic blocking of the low-level easterlies as proposed by Wexler (1961) or by upper-level westerlies and the lee cyclogenesis (Uccellini and Johnson 1979; Uccellini 1980; Byerle and Paegle 2003; Mo and Berbery 2004). This study is an attempt to distinguish among the different mechanisms using a general circulation model (GCM) and the linear and nonlinear diagnostic models.

We emphasize the time mean LLJ throughout this study. Although the diurnal variation is a prominent feature of the Great Plains LLJ, the total moisture transport over the Great Plains region is dominated by the time mean moisture transport from the Gulf of Mexico by the
mean LLJ (Barlow et al. 1998). Understanding the interannual variation of the LLJ is the ultimate goal and one that can significantly improve the predictive skill of the summer U.S. precipitation. But it is difficult to understand its variability without a solid understanding of the existence of the climatological LLJ in the first place.

In the next section, the Geophysical Fluid Dynamics Laboratory (GFDL) GCM experiments and the linear and nonlinear stationary wave models will be briefly described. In section 3, we show the main results of the GCM experiments and the stationary wave model diagnostics. Finally in section 4, we summarize our results, discuss the implications of the results, and possible future research.

2. Methods

a. GFDL model and experimental designs

The Atmospheric General Circulation Model (AGCM) used in this study is the new generation of the global atmosphere and land model developed at GFDL for climate research and climate prediction applications. The atmospheric model, known as AM2, includes a gridpoint atmospheric dynamical core, a fully prognostic cloud scheme, a moist turbulence scheme, multispecies aerosol climatology, and components from previous models used at GFDL. The model also contains the diurnal variation of the solar radiation. The model uses the staggered Arakawa-B grid with 2° latitude by 2.5° longitude horizontal resolution. In the vertical, it uses 24 hybrid sigma-pressure levels, including nine full levels below 1.5 km. The high vertical resolution in the planetary boundary layer may be important for a good simulation of the LLJ, given the discussion in the previous section.

The land model, known as LM2, includes soil sensible and latent heat storage, groundwater storage, and stomatal resistance. Compared to the previous generation of the GFDL models, this newly developed AGCM has been shown to contain more capabilities and potential for climate simulations. More details about the model including the evaluation of model climatology and characteristics of interannual variability such as its response to ENSO can be found in Anderson et al. (2004).

The control GCM experiment includes complete earth topography and prescribed time-varying climatological sea surface temperature (SST; denoted as M experiment). The SST was taken from Reynolds’ Optimum Interpolation SST dataset (Reynolds and Smith 1994) and the monthly climatology of SST was obtained by averaging it from November 1981 to January 1999. In the second experiment, the model has realistic earth topography except those over the North American continent, which have been removed (denoted as nR experiment for no Rockies). Both experiments were integrated for 50 yr with the same prescribed climatological SST. The first two years of the integration was discarded for model spinup, and the model climatology was obtained by averaging over the last 48 yr. By comparing the two experiments, the role of the North American topography can be determined.

b. Linear and nonlinear stationary wave models

The linear and nonlinear stationary wave models were used extensively in diagnosing the maintenance of climatological stationary waves in both reanalysis and GCM experiments (Ting 1994; Wang and Ting 1999; Ting et al. 2001; Held et al. 2002), and anomalous stationary waves due to tropical heating (Ting and Yu 1998) and tropical sea surface temperature anomalies (Ting and Held 1990; Ting and Hoerling 1993). The linear stationary wave model is a steady-state model that uses the primitive equations linearized about the zonal mean basic state (Ting and Held 1990). The model is subject to the zonally asymmetric forcing, which includes the three-dimensional diabatic heating, the earth topography, transient flux convergences, and the stationary nonlinear terms (those terms ignored in the linearization). A stationary wave solution is obtained through matrix inversion. The nonlinear model is a time-marching model that has prescribed basic state (zonally symmetric or asymmetric) and it uses the same forcing as those in the linear model. The nonlinear model solution is obtained by integrating the nonlinear primitive equations to a steady state, which is achieved at around day 30 in this case. In both the linear and the nonlinear models, the model resolution is R30 in the horizontal and 14 unevenly spaced sigma levels in the vertical. The dampings applied in both the linear and nonlinear models include a biharmonic diffusion with the coefficient of $2 \times 10^{10}$ m$^2$ s$^{-1}$, and the Rayleigh friction and Newtonian cooling which has a damping scale of 0.3 days at the lowest sigma level and decreases to 15 days in the free atmosphere. Because of these dampings applied, the baroclinic eddies are effectively suppressed in the nonlinear model. The results from the nonlinear model are shown by the averages from day 41 to 50 of the daily output. For further details of the linear stationary wave model, see Ting and Held (1990), and for the nonlinear model, Ting and Yu (1998).

3. Results

a. GCM responses

Figure 2 illustrates the 850-mb wind vectors for the M experiment (Fig. 2a), the nR experiment (Fig. 2b) and
the difference between M and nR experiments (Fig. 2c) averaged for June, July, and August and over a 48-yr period of the model integration. The corresponding precipitation is shown in Fig. 3. In the M experiment, the time mean Great Plains LLJ is well simulated by the GFDL model (comparing Fig. 2a to Fig. 1d). The magnitude of the maximum LLJ is slightly stronger and located further north in the GCM (Fig. 2a) compared to observations (Fig. 1d). In the absence of the North American topography, the time mean LLJ is almost nonexistent over the Great Plains region (Fig. 2b). The strong easterlies along the southern flank of the Atlan-
tic subtropical high continue westward from the Caribbean to the eastern Pacific (Fig. 2b), rather than bending northward as in the case with full topography (Fig. 2a). Since the GFDL model is able to simulate the Great Plains LLJ reasonably well, the lack of time mean LLJ in the nR experiment provides a useful tool to understand the physical mechanisms responsible for the existence of the time mean LLJ.

The lack of the LLJ resulted in a dry region over the Great Plains and enhanced rainfall over the Gulf coast (Fig. 3b) as compared to the M experiment (Fig. 3a). The difference between M and nR experiments (Fig. 3c) shows a north–south dipole with enhanced precipitation to the north and reduced precipitation to the south. Further calculation of the moisture transport shows that the reduction in precipitation over the Great Plains in the nR case is mainly a result of the lack of moisture transport by time mean flow, rather than by transient eddies (not shown).

### b. Linear model results

We apply the linear stationary wave model linearized about the GCM’s zonal mean zonal flow (Ting and Held 1990) to determine the physical mechanisms by which the presence of the North American topography changes the low-level flow. We first computed the linear model response to the total stationary wave forcings (heating, topography, transients, and stationary nonlinearity) in M and nR cases. The linear model is found to be able to simulate the GFDL GCM’s low-level wind field and streamfunction very well in both the M and the nR experiments. Figure 4 shows the JJA zonally asymmetric 850-mb wind vectors and streamfunction for the M (Figs. 4a,b), nR (Figs. 4c,d), and the difference between M and nR experiments (Figs. 4e,f) in GCM (left panels) and the linear model forced by total stationary wave forcing (right panels). The main features of the 850 mb stationary waves in the GCM M experiment (Fig. 4a) are the strong subtropical highs over both the North Atlantic and the North Pacific, and a relative low pressure center over North America. In the absence of the North American topography (Fig. 4c), the strength of the subtropical highs over both the Pacific and Atlantic remains almost unchanged. Rodwell and Hoskins (2001) gave a detailed account of the various forcing mechanisms responsible for the existence of the oceanic subtropical highs. The GCM results here suggest that the effect of the North American topography in maintaining the strength of the subtropical highs over both the Pacific and Atlantic is negligible. The dominant effect of the topography on the low-level stationary waves is to force a cyclonic center directly over the Rockies (Fig. 4e) and the weak anticyclone east of the Rockies over the Gulf of Mexico and eastern United States. This cyclone/anticyclone pair supports the presence of the strong LLJ centered at 100°W between 20° and 45°N. An anticyclone center is also found further north over Gulf of Alaska and North Atlantic in Fig. 4e. All of the features noted above were accurately simulated by the linear model (Figs. 4b, d, f), thus allowing further decomposition of the different forcing effects.

The linear responses to heating, topography, transients, and the stationary nonlinearity due to the presence of the North American topography (M-nR) are shown in Figs. 5a–d, respectively. Both the linear effect of the heating (Fig. 5a) and that of topography (Fig. 5b) tend to produce anticyclonic responses over the U.S., inconsistent with the cyclonic response in the GCM (Fig. 4e). The linear response to transients (Fig. 5c)
Fig. 4. The zonally asymmetric 850-mb streamfunction (contours) and wind vectors for (a) GFDL GCM with full topography, (b) linear model simulation of (a), (c) GCM without North American topography, (d) linear model simulation of (c), (e) difference between GCM with and without North American topography, and (f) linear model simulation of the difference. Contour interval is $2 \times 10^6$ m$^2$ s$^{-1}$ and negative contours are dashed. Shading indicates the mountain heights (in meters) used in the corresponding experiments.
shows a weak dipole with anticyclone to the northwest and cyclone over the central United States. But the strengths of both centers are much weaker than and the location of the cyclone does not coincide with that in GCM. The cyclonic response over North America is entirely due to the stationary nonlinear effect, as is clear from Fig. 5d. The anticyclonic responses over the Gulf of Alaska and North Atlantic in Figs. 4e and 4f can be mostly explained by the stationary nonlinear effect (Fig. 5d) as well. The stationary nonlinearity contains all the nonlinear terms that are ignored while linearizing the primitive equations about the prescribed zonal mean climatological basic state. The exact physical mechanisms responsible for the stationary nonlinearity are not clear from the linear model diagnostics alone. The linear model results do suggest that while the forcing of the LLJ is clearly nonlinear, the response to that forcing is linear. To explore the nature of the nonlinear forcing, it is necessary to use a fully nonlinear model, which will be explored next.

c. Nonlinear effect of topography

The linear response to the North American topography (Fig. 5b) depicts the effect of the zonal mean zonal flow, including the easterlies in the Tropics and westerlies in the midlatitudes, impinging on topography and producing an anticyclone right on top of the North American Cordillera for both the Tropics and the midlatitudes (see, e.g., Fig. 12a of Rodwell and Hoskins 2001). This linear response is consistent with the linear baroclinic theory for the midlatitude response and the linear barotropic theory for the tropical responses (Hoskins and Karoly 1981, their Fig. 7). Since mean temperature gradients are much weaker in the Tropics, barotropic theory is more applicable to the tropical easterlies impinging on the Sierra over Mexico. From the linear model results in the previous subsection, we learnt that the stationary nonlinearity is an important forcing, thus suggesting an examination of the role of topography in a fully nonlinear model. The nonlinear effects of the heating and transients will be examined in the next subsection.

Figure 6a shows the zonally asymmetric streamfunction and wind vectors at 850 mb from the nonlinear model response to the North American topography when the basic state is taken from the zonally averaged zonal flow from the nR experiment. It should be pointed out that we choose the basic state from nR experiment in the nonlinear model because the North American topography is the forcing, thus its effect should not be included in the basic state. Figure 6a can be compared directly to Fig. 5b, with the only difference being the inclusion of the nonlinear terms in Fig. 6a. The nonlinear model response to the North American topography consists of an anticyclone on top of the Rockies over western Canada and a cyclone center further east, and a broad weak cyclone region over the
western U.S. The key difference between the linear response (Fig. 5b) and the nonlinear response (Fig. 6a) to North American topography is the change from anticyclone to cyclone over the southwest United States and northeast Mexico. The difference is mainly a result of the fact that in the nonlinear model, flow impinging on the North American Cordillera is allowed to go around the mountains because isentropes can intersect the mountain (Rodwell and Hoskins 2001). The midlatitude westerlies north of 40°F tend to turn both northward and southward. Under the potential vorticity conservation constraints \[ \left( \frac{f + \zeta}{H} \right) = \text{const.} \], the northward-flowing branch generates anticyclonic vorticity because of the increases in planetary vorticity, while the southward flowing branch generates cyclonic vorticity due to the decrease of planetary vorticity. Since the response of the northward flowing branch is consistent with the linear response, the nonlinear model only enhances the linear model response north of 40°N, while the southward branch creates a cyclonic center over the Rockies that is different from the linear response. For the tropical easterlies flowing toward the Sierra Oriental in Mexico, the nonlinear flow tends to move northward along the mountain and anticyclonic shears are created because of the increase of planetary vorticity. The southward flow on the west coast and northward flow along the Sierra Oriental form a low right above the Rockies. The nonlinear model response to the North American topography (Fig. 6a), although of the right sign compared to the corresponding GCM response (Fig. 4e), is very weak. Figure 7a illustrates the total streamfunction and wind vectors at 850 mb, which includes the zonally symmetric basic state and the nonlinear model response to topography, and is very similar to the schematic depiction of Rodwell and Hoskins (2001, their Fig. 12b) for the nonlinear response to topography. The low-level flow over the southern Great Plains, although southerly in direction, is too weak to account for the LLJ found in the mountain experiment (Fig. 4a).

The amplitude of the responses can be much stronger if we consider the fact that, in the real world, the flow that interacts with the North American topography is not the zonal mean one, but one that is three-dimensional and contains the zonally asymmetric component. For example, one can imagine that the full effect of the North American topography can be obtained by placing the topography in a basic flow that has no effect of the North American topography (nR; Fig. 2b). The strong easterlies associated with the southern flank of the North Atlantic subtropical high in the absence of the North American topography encounters the eastern slope of the Sierra Oriental and turn northward. As it

Fig. 6. The zonally asymmetric streamfunction (contours) and wind vectors at 850 mb from the nonlinear model response to North American topography when the topography forcing is superimposed on basic states taken from the GCM experiment without the North American topography. (a) zonally averaged basic state. (b) full three-dimensional basic state, (c) zonally averaged basic state over the Atlantic domain and full three-dimensional basic state over the Pacific domain, and (d) zonally averaged basic state over the Pacific domain and full three-dimensional basic state over the Atlantic domain. Contour interval is 1 × 10^6 m^2 s^-1 and negative contours are dashed. Shading in (b) indicates the terrain heights (in meters).
turns northward, it obtains anticyclonic vorticity. At the same time, strong midlatitude westerlies over the North Pacific encounters the North American Cordillera and turn both northward and southward, producing anticyclonic and cyclonic vorticity, respectively, similar to the zonal mean basic-state case. The nonlinear model response to the North American topography given the full nR basic flow is shown in Fig. 6b. A strong cyclonic region develops over the Rockies and weak anticyclone centers exist over the eastern United States and the Atlantic, consistent with the above argument. Figure 6b is very similar to the response to North American topography in the GCM (Fig. 4c) and the linear response to stationary nonlinearity (Fig. 5d), suggesting that the dominant contribution of these responses is from the nonlinear response to topography in the three-dimensional basic flow. Figure 7b shows the total flow in this case, including the three-dimensional nR basic flow (Fig. 2b) and the nonlinear response to topography (Fig. 6b), a strong LLJ is apparent and similar to that in the GCM with full topography (Fig. 4a).

Since both the North Pacific and the North Atlantic subtropical highs interact with the North American Cordillera, it is interesting to determine which one contributes to the formation of the Great Plains LLJ. To this end, we divide the nR basic flow into two parts, the Pacific flow, which contains the full three-dimensional nR basic state west of 100°W and zonal mean nR basic state east of 100°W, and the Atlantic flow, which contains three-dimensional nR basic state east of 100°W and zonal mean nR basic state west of 100°W. The nonlinear model responses to the North American topography superimposed on the Pacific and the Atlantic basic states are shown in Figs. 6c and 6d, respectively. While the cyclonic region on the west coast of the United States is largely due to the three-dimensional nR Pacific flow, the LLJ and the associated cyclone and anticyclone pairs over the United States are entirely due to the three-dimensional nR Atlantic basic state, consistent with the trade wind mechanism proposed by Wexler (1961). The associated total flow fields for the Pacific and the Atlantic basic-state cases are shown in Figs. 7c and 7d respectively.

The implication of the above results, that is, the interaction between the three-dimensional flow and the North American Cordillera is largely responsible for the existence of the time mean LLJ, is that the variability of the mean LLJ, such as that shown in Fig. 1, may have been caused by the variability in the strength of the Atlantic subtropical anticyclones. The analysis of the linkage between Atlantic subtropical high intensity and the mean LLJ strength is currently under way and will be reported in a subsequent paper.

d. Nonlinear response to heating and transients

To test the mechanism of the thermal forcing due to topography on the generation of the LLJ (Holton 1967), we calculated the nonlinear response to the diabatic heating taken as the difference between M and nR experiments, when the forcing is superimposed on the

**Fig. 7.** Same as Fig. 6, except that the total flow including the basic state and the nonlinear model response is shown.
three-dimensional nR basic state. The results thus obtained indicate the role of North American topography when the presence of topography is only felt through its thermal effect (diabatic heating), that is, no mechanical forcing of the topography is included. Such a response is shown in Fig. 8a. While Fig. 8a differs from its linear counterpart in Fig. 5a, the streamfunction response in Fig. 8a is rather weak and the corresponding wind vector over the United States is largely showing a northerly component over the central United States, opposite to the direction of the Great Plains LLJ. Thus thermal forcing alone is not enough to generate the Great Plains LLJ. The precipitation difference in Fig. 3c suggests that there is a latent heat source over the northern plains and should play a role in forcing the southerly flow toward the heating center. However, a detailed examination of the heating vertical structure indicates a net cooling at the lower troposphere directly below the latent heat source. Thus the net effect of the heating and cooling is rather weak as indicated in Fig. 8a. Whether the low-level cooling is an artifact of the model or represents nature is not clear.

Similarly, we test the hypothesis that the upper-level jet streaks and lee-cyclogenesis in the presence of the North American topography may have contributed to the maintenance of the LLJ (Uccellini and Johnson 1979; Uccellini 1980). The nonlinear model response to transient forcing taken as the difference between M and nR experiments and superimposed on the three-dimensional nR basic flow is shown in Fig. 8b. While there is a significant northward flow over the United States in Fig. 8b, the southerly flow is located further east and north of the Great Plains LLJ in Fig. 2a. Thus transient eddy activities due to the presence of the North American topography may contribute to extend the LLJ further north and east, but it is not the dominant forcing mechanism for the generation of the jet. We conclude that both thermal forcing and transient eddy forcing due to the presence of North American topography play a secondary role in the generation and maintenance of the Great Plains LLJ.

4. Summary

We examine in this paper the role of the North American Cordillera in maintaining the low-level jet over the United States Great Plains during boreal summer. Atmospheric general circulation model experiments with and without the North American topography were carried out using the new generation of the GFDL climate model. The GCM results suggest that the existence of the time mean LLJ over the Great Plains is largely due to the presence of the North American Cordillera, including the Rockies and the Sierra Nevada in Mexico. In the absence of the North American topography, the time mean LLJ completely disappears over the Great Plains, and the U.S. precipitation shows a large increase over the coast of the Gulf of Mexico and decrease over the Great Plains.

The presence of the North American Cordillera can be felt by the atmosphere in several different ways. First, it acts as a physical blocking to the flows from both east and west of the mountains, forcing the flow to go over or around the topography. Second, the topography can interact with the upper-level jet streaks and produce lee-cyclone activities. To determine the dominant physical mechanism that is responsible for the Great Plains LLJ in the presence of the North American topography, such as the mechanical forcing, the thermal forcing or the modified transient eddy activities, we used the linear and nonlinear stationary wave models in this study. The linear model is able to simulate very realistically the GCM stationary waves with or without the North American topography when stationary nonlinearity is included as a forcing. Further decomposition reveals...
that the stationary nonlinearity is the most dominant forcing mechanism for the Great Plains LLJ, suggesting the nonlinear nature of the topographic forcing.

The nonlinear stationary wave model is used systematically to understand the mechanical forcing of the North American topography. When North American topography forcing is superimposed on the GCM’s zonally averaged flow taken from the experiment without the North American topography (nR) in the nonlinear model, the resulted low-level flow hints on the existence of the LLJ, but with much weaker amplitude compared to that in the GCM. When the North American topography is superimposed on the three-dimensional flow from the nR experiment, however, the nonlinear model reproduces the difference between GCM experiments with and without the North American topography very well, indicating the importance of the full trade winds in the tropical Atlantic and the midlatitude westerlies over the Pacific in interacting with the North American topography. Further decomposing the total GCM flow in the nR experiment into that over the Atlantic and over the Pacific indicates that the most dominant effect comes from the Atlantic trade wind interacting with the Sierra Oriental in Mexico for generating the Great Plains LLJ. This confirms the mechanism proposed by Wexler (1961) on the generation of LLJ through northward turning of the Atlantic trade wind upon encountering the east slope of the topography and the potential vorticity conservation constraint. The thermal and transient forcing due to the topography is found to be secondary compared to the mechanical forcing of the North American topography in the forcing of the Great Plains LLJ, although transient forcing is found to be contributing to the eastward and northward extension of the LLJ.

This study provides a thorough investigation of the previously proposed mechanisms for the generation of the Great Plains LLJ, but focusing on the time mean LLJ instead of the diurnal characteristics of the LLJ. The diurnal variation may be explained by the coupling/decoupling of the frictional boundary layer with the top of the boundary flow during the day/night. During the day, the strong surface heating makes the boundary layer highly unstable and thus well mixed, the surface friction is felt throughout the boundary layer. During the night, on the other hand, the cooling of the surface makes the boundary layer stable and thus the interior flow is decoupled from the surface friction, the LLJ attains a maximum at the early morning hours when the stabilization of the boundary layer reaches a maximum.

Our results suggest strongly that the trade wind associated with the southern flank of the North Atlantic subtropical high is the dominant factor determining the strength of the Great Plains LLJ. Figure 1 is suggestive that the strength of the trade wind over the Caribbean may have determined the strength of the Great Plains LLJ that leads to the major floods and drought over the United States Great Plains in 1993 and 1988, respectively. If so, it is important to understand the mechanisms that contribute to the variability of the North Atlantic subtropical high and the corresponding trade winds over the tropical Atlantic and the Caribbean. As shown in Rodwell and Hoskins (2001), the subtropical highs are partly maintained by the monsoonal heatings, indicating the possible role of remote heatings, particularly the tropical heatings, on the Great Plains LLJ. Furthermore, the effect of the Atlantic SST and its induced thermal forcing may also influence the strength of the subtropical high. Further analysis is needed to determine the dominant mechanisms contributing to the interannual variation of the North Atlantic subtropical high and the Great Plains LLJ. This is the subject of our future studies.

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