Variability of the Great Plains Low-Level Jet: Large Scale Circulation Context and Hydroclimate Impacts

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Abstract

Variability of the Great Plains low level jet (GPLLJ) and its relationship to large scale circulation patterns and hydroclimate impacts is analyzed using monthly data from the NCEP North American Regional Reanalysis (NARR) and the European Centre for Medium Range Weather Forecasts (ERA-40) reanalysis data. The GPLLJ plays an important role in supplying moisture to the central United States during summer but its monthly variability structure and mechanisms remain to be elucidated.

Features of the vertical jet-like monthly meridional wind profile and northward moisture flux distribution are used to define an index of GPLLJ variability, which exhibits variations on intraseasonal and interannual timescales.

Regressions of the GPLLJ index on geopotential heights reveal interesting links with larger scale circulation anomalies over the Pacific and Atlantic. GPLLJ regressions on SST and atmospheric diabatic heating suggest a Pacific basin origin for some of these anomalies. Such links have been noted before in context of warm-season hydroclimate variability over the Great Plains.

Empirical Orthogonal Function (EOF) analysis is conducted on May-July 900 hPa wind field in NARR and ERA40 to identify the recurrent patterns of variability. The first three modes in NARR are retained and each PC is regressed on precipitation to determine the linkage to this important hydroclimate field. It is found that the first three EOF’s contribute substantially to Great Plains precipitation variability. The EOF structures are fairly insensitive since the NARR (1979-2002) and ERA-40 (1958-2001) based analyses yield rather similar characteristics.

Notable findings include: The GPLLJ index shows robust correlations (0.71 with RBN 2005 July precipitation index) to Great Plains precipitation; The mid-latitude tropospheric wave anomalies associated with the GPLLJ suggest influence by the summertime NAO on GPLLJ variations and hydroclimate impacts; Recurrent modes of GPLLJ variability show meridional/zonal jet expansion and strength modulation with the first (second) modes linked to the flood (drought) of 1993 (1988) over Great Plains.
1. Introduction

The Great Plains region of North America extends from the interior Canadian provinces of Alberta, Saskatchewan, and Manitoba south through the west central United States into Texas. This area is a predominantly flat agricultural region in close proximity to the Rocky Mountains and the Gulf of Mexico. During the spring and summer large amounts of heat and moisture are transported north from the Gulf of Mexico into the central United States by the Great Plains low level jet (GPLLJ). These fluxes and their convergence exert profound influence on the hydroclimate of the Great Plains region by providing both the moisture and the necessary thermodynamic environment for precipitation formation.

The characterization of regional expressions of climate variability has recently been high priority in the U.S climate science program, as evidenced by the U.S. global water cycle initiative (Hornberger et al. 2001). Improved understanding of Great Plains hydroclimate variations is of great scientific and societal interests. Among the societal ones are agricultural productivity, water resource management, energy distribution and regional ecosystems. Scientists are interested in accurate descriptions of the observed regional variability structure and in understanding the involved mechanisms so that the potential of general circulation models (GCMs) in representing regional-to-continental scale features can be assessed. Such assessments are necessary for developing confidence in the GCM-generated regional climate change scenarios. The GPLLJ figures prominently in this scheme given the recent finding that moisture transport dominates local evaporation in the generation of Great Plains precipitation variability (Ruiz-Barradas and Nigam 2005; hereafter referred as RBN).

The GPLLJ is a persistent warm season climatic feature characterized by a low-level wind maximum located below 850 hPa. The jet is typically a nocturnal phenomenon however its
persistent occurrence during the warm season enables the jet signature to be manifest in the monthly averaged wind field. The GPLLJ has been shown to form due to supergeostrophic wind speeds as a consequence of the spatially uneven and diurnally varying heating of the terrain slope, boundary layer frictional effects, and inertial oscillation of the ageostrophic wind vector (Blackadar 1957; Holton 1967; Hoxit 1975; Wexler 1961). Uccellini and Johnson (1979) analyzed the symbiotic relationship of the GPLLLJ with upper level features and found a correlation between upper-level jet streaks and low-level jets. They attributed the correlation to the mass adjustment and indirect circulation during severe weather episodes over the Great Plains. Their analysis showed that the GPLLJ was influenced by synoptic scale features in addition to diurnal heating variations.

While diurnally varying boundary layer influences are important for the diurnal variability of the low level wind field, the larger-scale flow (e.g., the monthly and/or seasonal fields) constitute the background circulation on which the diurnally varying influences operate. Observational and modeling studies have recently been focusing on the mechanical influence of the North American Cordillera on the time mean GPLLJ. Byerle and Paegle (2003) using the NCEP/NCAR reanalysis show the influence of the western North American topography in focusing global scale features of the ambient flow into regional responses, and in particular the GPLLJ. Stationary wave modeling experiments show that the mechanical blocking of the Atlantic trade winds and potential vorticity conservation is the primary mechanism for forcing the time mean GPLLJ and that the diurnally varying thermal characteristics are secondary (Pan et al. 2004; Ting and Wang 2006).

In view of these findings it is important to ascertain the structure, origin, and the regional impact of the low-frequency variations of the GPLLJ, (i.e., of the monthly/seasonal jet anomalies). Seasonal and subseasonal strength of the GPLLJ has indeed been shown to be correlated to Great Plains

The hydroclimate of the Great Plains has been a topic of great societal and scientific interest in recent years due to the occurrence of drought (flood) in 1988 (1993). Anomalous warm-season precipitation over the United States has been linked to large-scale circulation variability having origins in the Pacific basin and separate but contemporaneous variations of the GPLLJ (Mo et al. 1995; Bell and Janowiak 1995; Trenberth and Guillemot 1996; Mo et al. 1997). The Atlantic basin’s role in Great Plains hydroclimate variability through GPLLJ induced moisture transports was noted in (RBN).

The GPLLJ’s influence on moisture transports and low-level moisture flux convergence, coupled with the growing evidence from observational and modeling studies for the remote influences on Great Plains precipitation, calls for characterization of the recurrent structure of GPLLJ variability and of its dynamic and thermodynamic links to remote regions. Specific questions examined here include:

- How is the GPLLJ variability linked to larger scale circulation variations? Observation and modeling analyses of warm season circulation variability show coherent stationary wave patterns in the Pacific North American region. Are some of these patterns of consequence for the GPLLJ?
- What is the structure of regional precipitation anomalies associated with GPLLJ variability?
- What are the recurrent patterns of GPLLJ variability? Does the jet-core expand meridionally or zonally? Which of these patterns is of consequence to Great Plains rainfall variability?
This past decade has seen the release of atmospheric and oceanic reanalysis datasets. The first of these was the NCEP/NCAR reanalysis (Kalnay et al. 1996). The reanalyses are produced using a fixed data assimilation scheme so as to minimize the influence of model evolution, and to potentially include observations that could not be reported in real time. The NCEP/NCAR global reanalyses was able to capture many climatological features of the GPLLJ (Anderson and Arritt 2001). However due to coarse spatial and temporal resolution (5.0° longitude x 2.5° latitude, 17-level, 6-hourly) of the original NCEP/NCAR reanalysis some aspects of the climatological GPLLJ were misrepresented, especially the height, intensity, and frequency of the LLJ variations.

In contrast with the global reanalysis, the recently released North American Regional Reanalysis (NARR) has much finer spatio-temporal resolution and also benefits from improvements in data assimilation strategies. Indeed a salient feature of NARR is the direct assimilation of precipitation. A more realistic representation of precipitation would very likely improve the quality of surface fluxes of heat and moisture, which have been found important for LLJ evolution in mesoscale modeling experiments (Zhong et al. 1996; Zhang et al. 2006). NARR is thus considered an improvement over the NCEP/NCAR global reanalysis, especially in context of regional hydroclimate studies.

The goal of this study is to uncover the monthly variability structure of the GPLLJ in NARR and investigate the larger-scale circulation context and origin of GPLLJ variability on monthly/seasonal time scales using this unique dataset. The related hydroclimate impacts and their generation mechanisms are also key objectives of this study.

The present study’s unique attributes are:

- Use of high-resolution regional reanalysis data record (24 years) in studying seasonal and interannual variability of the GPLLJ.
• Creation of a GPLLJ index to study interannual variability.
• Characterization of GPLLJ connections to local and larger-scale circulation features, residually diagnosed diabatic heating, SSTs, and Great Plains hydroclimate.
• EOF analysis of GPLLJ variability in extended data records to diagnose recurrent variability patterns, associated precipitation, and circulation features.

The present paper is in some sense, complementary to the study of RBN, in that a more circulation-centric analysis strategy is adopted here. This strategy is, in fact, suggested by the precipitation-centric analysis of RBN, which showed remote water sources to be very important for Great Plains hydroclimate variability. As the water from remote regions (e.g., Gulf of Mexico) is transported into the continental interior, most effectively, by the GPLLJ, this circulation feature, primarily, its variability is the focus of the present study, in an effort to understand the origin of warm-season hydroclimate variability over the Great Plains; the ultimate objective.

Section 2 will detail the data sources and methods used in this study. In section 3, the low-level flow structure and moisture flux characteristics associated with the GPLLJ are discussed. Sections 4 and 5 present the GPLLJ index and regressions on large-scale climate features and precipitation respectively, while section 6 discusses the recurrent variability patterns of the GPLLJ and their influences on Great Plains hydroclimate. Section 7 provides a brief summary of findings and suggestions for future work.

2. Data Sets and Methodology

a. Data Sets

The North American Regional Reanalysis (NARR) is a 25-year (1979-2003), consistent, high-resolution dataset that covers the North American domain. The NARR dataset is similar to the
The original NCEP/NCAR global reanalysis, however includes several improvements. Most of these lend themselves nicely to the study of long-term mesoscale variability and the impacts on hydroclimate. The most striking difference between the NARR and the NCEP/NCAR reanalysis is the spatio-temporal resolution upgrade; NARR has a 3-hour analysis cycle and 32 km horizontal resolution. There are 13 vertical levels below 700 hPa, which is ideal for capturing LLJ characteristics. Additionally, NARR assimilates direct observations of precipitation over land whereas the NCEP/NCAR reanalysis archives precipitation obtained from 6-hour forecasts initialized by NCEP reanalysis fields. NARR also takes advantage of the regional ETA model including many of the upgrades that were made to this model and the data assimilation scheme.

The ERA-40 is a global reanalysis project with output spanning the period September 1957-August 2002 produced at ECMWF. It is comprised of conventional observations and satellite data streams. Analyses were produced at 6 hourly intervals for the entire time period and archived on a 2.5° longitude x 2.5° latitude horizontal grid. There are 23 vertical isobaric levels from 1000 hPa to 1 hPa with 12 levels below 150 hPa.

**b. Methodology**

Climatological analysis is performed on monthly averaged meridional wind and column integrated moisture fluxes. Column integrated meridional moisture flux is defined as the mass weighted vertical integral of meridional moisture flux between 1000 and 700 hPa. A GPLLJ index is defined based on departures of the meridional wind from their 1979-2002 climatology. Monthly regressions are computed on selected fields including vertically averaged diabatic heating from the ERA40 reanalysis and SST’s obtained from the Hadley Centre sea ice and SST analysis. Diabatic heating was diagnosed residually from ERA40 data using the thermodynamic equation (Chan and Nigam 2006). To identify recurrent GPLLJ variations, Empirical orthogonal function (EOF)
analysis is performed on 900 hPa monthly meridional winds over the Great Plains. The EOF’s are unrotated and their principal components are used as indices for regression analysis. The EOF analysis was undertaken to identify the recurrent sub-continental scale circulation patterns operative in the warm-season, and to assess their specific contributions in modulation of the GPLLLJ as manifest in GPLLLJ index variations.

3. Low Level Flow Climatology

a. Mean Meridional Wind Profiles

Figure 1 shows longitude-height cross sections of the warm season evolution of the monthly averaged meridional wind at 25°N and 30°N; alternate months beginning with May are shown. Significant vertical wind shear is present above the core at both 25°N and 30°N in all months except September. As the warm season progresses, the average low level maximum in meridional flow increases, reaching a peak in July. There are significant structural differences between the two latitudes, e.g., the meridional wind core is located between 900-950 hPa at 25°N but somewhat higher (900-850 hPa) at 30°N. The tightly packed core at 25°N is perhaps more indicative of LLJ location in view of steep topography to the west. Topography has been noted to have an impact on the LLJ as these areas can generate shallow baroclinicity (e.g., Zhang et al 2006). At 30°N, the core has shifted to the west and exhibits a less steep eastward-downward slope, reflecting the influence of the more gently sloping terrain and related thermal characteristics. It is noteworthy that the seasonal decay of the LLJ in August-September is quite gradual at 30°N, in comparison with the precipitous decay at 25°N. The influential east-west temperature gradient at 25°N (but not at 30°N) is determined by the Gulf of Mexico waters which have warmed up by
late summer/early fall; leading to a weakened gradient and notable differences in seasonal evolution at the two neighboring latitudes.

\textit{b. Diurnal Cycle of Meridional Wind}

Figure 2 displays longitude-height cross sections of July meridional wind (contoured) and temperature (dashed) at the time of maximum (7 AM CDT) and minimum (4PM CDT) magnitude. There are considerable differences in the strength of meridional wind between early morning and late afternoon. Some previous studies have noted a doubling of the daytime wind speed at night (Stensrud 1996). NARR does not produce such a strong diurnal oscillation in the time-averaged flow at 25°N. Average meridional wind speeds range from 6 m s\(^{-1}\) at the time of local minimum to 10 ms\(^{-1}\) during local maximum, which is considerable but not quite double. The monthly average across the eight 3-hourly apart NARR time steps is closer to the 7 AM monthly mean at 25°N; suggesting that the jet is generally strong over many of the 8 time steps. However at 30°N the range is from 4 ms\(^{-1}\) to 10 ms\(^{-1}\) which is more than double. This suggests that at lower latitudes the diurnal oscillation in low-level flow is not as strong as that of northerly latitudes. The thermal structure shows significant diurnal variations especially at 25°N. During the afternoon the isotherms slope down toward the plain while in the early morning hours before sunrise there is a warm dome along the eastern slope of the mountains above 950 hPa. Below this level the situation is however reversed.

Although tempting, one must not readily indulge in verification of thermal wind balance in the superposed structure of meridional wind on the east-west running isotherms in figure 2. The extent to which geostrophic balance and thermal wind relationship hold in the PBL region and at the sub-synoptic scales of the GPLLJ is, presently, under investigation.
Should the thermal wind relationship hold, the eastward down sloping isotherms in figure 2 would imply a northerly thermal wind, and thus a diminished GPLLJ in case of steeper isotherms; consistent with diurnal variations depicted in figure 2, especially at 25°N. Note, the isotherms are not only less steep during early morning, but their east-west gradient changes sign below 950 hPa in the vicinity of topography. The location of the jet-core near this level is again, not inconsistent with thermal wind balance considerations.

c. Meridional Water Vapor Flux

The primary impact of the GPLLJ on hydroclimate is through the column integrated meridional moisture flux. A benefit to viewing the climatological jet in terms of the column integrated meridional moisture flux is two fold: The spatially varying vertical range of the LLJ core fluctuation is encompassed by the vertical integral, and the jet’s influence on central U.S. hydroclimate is readily apparent.

Figure 3 depicts the evolution of integrated meridional moisture flux throughout the warm season in NARR. Enhanced meridional moisture fluxes can be seen in various locations. Modest inflow from the Gulf of Mexico occurs in mid spring and increases throughout early summer reaching a peak of 180 kg m\(^{-1}\) s\(^{-1}\) over extreme northeastern Mexico in July, when its northward reach into the southern and central Great Plains is also greatest. The moisture fluxes associated with monsoonal flow over the southwest U.S. in late summer are captured nicely as are the fluxes associated with the westward flank of the Bermuda high, which skirt the eastern seaboard in boreal summer months.

This meridional moisture flux view of the GPLLLJ is consistent with the earlier meridional wind based depiction (c.f Fig. 1), in that the jet-core is located at ~25°N with a north-westward tilt in both descriptions. If meridional moisture fluxes over southeastern Mexico and southern/central
U.S. are influenced by the diurnally varying GPLLJ, then these fluxes must exhibit a diurnal cycle as well. Figure 4 shows the diurnal amplitude and phase of the monthly and vertically integrated meridional moisture flux in NARR for May, July, and September, as diagnosed from harmonic analysis. The length of the arrow indicates flux-magnitude, while the arrow’s direction illustrates the time of day when this flux is a maximum. For example, an arrow pointing directly northward indicates that the flux is a maximum at 6 AM CDT.

Northward moisture fluxes are evidently strongest in July over both land and water. Over the Gulf of Mexico (and California) and over the southern tier states, the northward flux is strongest at midnight, but fluxes over the central United States are at their maximum in the wee hours of the morning (~ 6 AM CDT). The reason for clockwise veering of the arrows with increasing latitude over central U.S. is not clear at present; although most of the diurnal signal comes from the diurnal variability in meridional wind. The diurnal variability of specific humidity was found to be negligible.

4. Low-Level Jet Index

a. Index Definition

To facilitate the study of GPLLJ variability, an index was constructed from the areal average of meridional wind in the 102°W-97°W and 25°N-35°N box. The 5x10 degree latitude longitude box was chosen since it encompasses the salient features of the meridional wind and moisture flux climatologies, including majority of the local maxima ¹. The choice of vertical level for index definition is based on inspection of the vertical profile of the area averaged meridional wind.

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¹ Sensitivity to the longitudinal range was checked. Correlations of indices generated with slightly shifted boxes were on the order of 0.95. Note the coarser resolution Bonner (1968) GPLLJ climatology indicated 95-100° W as the area of maximum meridional wind; i.e. very close to the longitude range identified here.
Figure 5 shows the monthly April-August profiles from the NARR dataset, and also the July profile from ERA-40, for comparison. All profiles exhibit a classic LLJ structure. The coarser vertical resolution (75 hPa) ERA-40 reanalyses places the wind maximum at the 850 hPa level and is a bit challenged in depicting the vertical shear, especially in comparison to the 25hPa resolution NARR representation. In all months the maximum low-level meridional flow occurs at 900 hPa in NARR. Additionally, the strongest meridional wind profiles occur during the months of May, June, and July (MJJ). We thus define the Great Plains low-level jet index as the average 900 hPa meridional wind in the 25-35° N and 102-97° W box.

b. Index Variations

Figure 6 shows a plot of the GPLLJ index anomalies from NARR and ERA-40 datasets. The first two panels show the ERA-40 index anomalies; the display is broken into two panels to facilitate comparison with the NARR index anomalies (shown next). The bottom panel plots the NARR index anomalies in during the NARR-ERA40 overlapping period (1979-2001). The GPLLJ index has substantial intraseasonal variability, switching sign in 28 of the 40 ERA40 summers. During the overlapping period, the ERA-40 index exhibited 16 sign changes as opposed to 14 in NARR. Index variations in both NARR and ERA40 are strong and reasonably consistent. The index standard deviation is 0.98 in ERA40 and 1.20 in NARR. The correlation during the overlapping period is a robust 0.97 suggesting similar skill in tracking GPLLJ variations. The monthly May-July (July only) GPLLJ and Great Plains precipitation index (as defined in RBN) is correlated at 0.55 (0.71).

An interesting feature of the GPLLJ index is its characterization of the drought of 1988 and the flood of 1993. The index is most negative in June 1988 in the overlapping data period; negative

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2 Please note that 925 hPa was used in lieu of 900 hPa in calculating the ERA-40 GPLLJ index as 900 hPa data is unavailable in ERA-40.
index denotes a weakened GPLLJ and reduced northward moisture flux. On the other hand the index is very large and positive in June and July of 1993; indicating a stronger jet and associated moisture transports.³

Interannual variability is highlighted by the solid continuous bold lines, which are generated by a 1-2-1 smoothing of the warm season (MJJ) index averages. Viewed in this manner, the GPLLJ exhibits a weakening trend through the 1980’s, and was weakest in 1988. The opposite trend - jet strengthening - has been prevailing since then.

5. GPLLLJ Linkages

a. Index Regressions

Indices are attractive in that they can be used for compactly characterizing a phenomenon over a spatially coherent region and facilitate the uncovering of links with other important fields. With July exhibiting the maximum in GPLLJ amplitude, only July index values are used in computing regressions ⁴.

The NARR index regressions on the 900 hPa NARR meridional wind are shown in fig. 7a. Southerly anomalies are seen over much of the central U.S. and are accompanied by northerly anomalies off of the east and west coasts of Canada; suggesting the strengthening of the GPLLJ occurs in context of a continental scale circulation anomaly. The GPLLJ index regressions on NARR and ERA40 precipitation are shown in figs. 7b,d, respectively. The precipitation regressions differ considerably in both structure and magnitude; not surprisingly, since NARR assimilates observed precipitation, while ERA-40 generates it in a forecast mode. The GPLLJ is

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³ It is interesting to note that the extremely high index value in 1996 was not coincident with an anomalously wet summer, (c.f. Fig 3a in RBN 2005).
⁴ A separate nocturnal monthly index was also considered for regression analysis. No appreciable differences were found between the two monthly index regressions. Due to the monthly nature of the present study it was decided to use an index based on monthly and diurnally averages.
associated with Great Plains precipitation anomalies of up to 1.6 mm day$^{-1}$, which are located northward of the region that defines the LLJ core. The July climatological value of Great Plains precipitation is 3 mm day$^{-1}$ so this anomaly is significant. The location of the precipitation anomaly – downstream of the GPLLJ anomaly – is consistent with the finding of many studies, showing low-level convergence and vertical motions in the LLJ exit region. Oppositely signed but smaller magnitude anomalies are present over the southeastern United States and Gulf of Mexico.

Panels c and e in figure 7 show the GPLLJ index regressions on 200 hPa height and SLP in ERA40$^5$. The structure of the July height regression shows a coherent wave pattern over the Pacific/North American region, and also the mid latitude Atlantic basin. The pattern suggests the possibility of GPLLJ variability being influenced by summertime teleconnection patterns, assuming that these anomalies have robust footprints in the lower troposphere. The background flow can easily be altered in that case.

Using a GCM and a linear baroclinic model Ting (1994) showed that the climatological summertime stationary wave pattern was forced by west Pacific diabatic heating and amplified by continental topography. Specifically noted was the occurrence of a topographically forced wave train (an alternating high-low-high pattern) emanating from the Rockies, with downstream extensions over the southeastern U.S and the North Atlantic. An enhancement of this very feature is seen in the regression pattern here. Liu et al. (1998) used a linear model to study stationary wave forcing in relation to the Midwest drought and floods of 1988 and 1993 respectively. The observed 200 hPa height anomalies in the PNA sector during the summer of 1993 (c.f. Liu et al., figure 3) are almost identical to those shown in figure 7c except for amplitude differences.

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$^5$ ERA40 fields are used in regression analysis in order to identify the hemispheric-wide linkages; something not feasible with the regional NARR data set.
The sea level pressure anomalies associated with GPL LJ variability (Fig. 7e) shows a coherent pattern in the PNA region that mirrors the 200 hPa height anomaly pattern. This equivalent barotropic structure of the anomalies – a characteristic feature of propagated stationary waves – in the PNA sector supports the case for remote forcing of GPL LJ variability. The GPL LJ related anomalies in the Atlantic also exhibit equivalent barotropic structure, notwithstanding the weak 200 hPa high over northeastern Canada.

The sea level pressure anomalies (fig 7e) associated with GPL LJ variability in the Atlantic show a coherent pattern that is reminiscent of the North Atlantic Oscillation (NAO) in July. The NAO is generally associated with winter climate variability, although recently, its impact on warm season rainfall in the central/eastern United States has been noted (RBN 2005). The NAO index is usually defined as the difference of normalized sea level pressure anomalies at Iceland and the Azores (e.g., Hurell 1995). This definition is based on the structure of sea-level variability in winter; and as such, may not be suitable for defining NAO variability in summer. This difficulty is circumvented by using the Climate Prediction Centers’ index of summertime NAO variability (http://www.cpc.ncep.noaa.gov/data/teledoc). The index is based on principal component analysis of monthly 700 hPa height anomalies in summer, and as such, appropriate for use here.

The NAO’s influence on GPL LJ variability is directly assessed in Figure 8, which shows the July NAO index regressions on 200 hPa height in ERA40 (top panel), 900 hPa meridional winds in NARR (middle panel), and NARR precipitation (bottom panel). The spatial correlation (20-70°N, 120-360°W) of the NAO 200 hPa pattern with that in figure 7 is -0.85. However, there are significant differences in the amplitude of the two patterns, notably in the northwest of Greenland. The NAO index regression on 900 hPa meridional wind and precipitation from NARR exhibits a

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6 The positive height anomalies in the region are not fleshed out, perhaps, because the 200 hPa level is above the tropopause here.
cohesive structure similar to, except for the sign, to that displayed in figure 7 a and b. The NAO can modulate the strength and spatial extent of the summertime Bermuda high and as such impact low-level winds and moisture transports into the continent. The July GPLLJ and NAO indices are correlated at –0.46.

Although coherent wave patterns in the Pacific and Atlantic sector in figures 7-8 make the case for remote forcing of GPLLJ variability, the nature/location of the forcing that generate these coherent wave patterns (and GPLLJ variability) remains to be elucidated. The nature of the forcing is investigated in figure 9 by showing the July GPLLJ index regressions on some potential forcing fields: vertically averaged diabatic heating (top panel) from ERA40 and SSTs (lower panel) from the Hadley Center. Significant diabatic heating anomalies are present in the central (and eastern) tropical Pacific as well as over the Nordeste region of Brazil. The structure of heating anomalies, including diminished heating over Nordeste, is somewhat reminiscent of the ENSO-related heating distribution, the most common descriptions of which are for the winter season (e.g., Nigam et al 2000). The potential of the tropical heating anomalies (fig 9a) in generating coherent wave patterns that impact the GPLLJ remains to be ascertained, although Ting’s (1994) analysis of the influence of Pacific SST anomalies and Ding and Wang’s (2005) recent analysis linking Great Plains precipitation with a circumglobal teleconnection pattern emanating from Asia are encouraging in this regard.

The SST pattern associated with GPLLJ variability in July is shown in the bottom panel of figure 9. Although it is somewhat difficult to characterize the SST anomaly pattern in the Pacific, several features do resemble the post-mature phase of ENSO variability, e.g., the SST anomaly pattern in summer following the ENSO peak-phase (c.f. Nigam et al 2006). Some contribution from other modes of Pacific SST variability, including decadal ones, cannot be ruled out though.
The longitudinal distribution of the heating anomalies in the tropical Pacific (shown in the top panel) is in accord with the underlying SST distribution; recalling the warm-west and cool-east Pacific SST climatology, which introduces a westward bias in the position of diabatic heating (and rainfall) anomalies vis-à-vis SST anomalies; given the SST-threshold condition for occurrence of deep convection (e.g., Graham and Barnett 1987).

6. Structure of Recurrent Low-Level Flow Variability

a. Spatial patterns and PC time series

A drawback associated with index regressions is that the gleaned information sometimes provides inadequate insight into the operative mechanisms, especially if competing influences are at play. This motivates the use EOF analysis to identify the recurrent patterns of variability, each supposedly having its own generation mechanism. The analysis was conducted on monthly 900 hPa NARR meridional winds in the 105-85°W and 20-50°N domain, for the May, June, and July months. The domain was chosen to fully encompass both the jet core and its precipitation impacts. The left column of figure 10 displays the climatological MJJ 900hPa meridional wind (>5 m s⁻¹ shaded) and the first three EOFs (contoured); the right column shows the corresponding principal components (PCs). The three leading EOFs explain 37.8%, 23.3%, and 12.2% of the regional wind variances respectively.

The leading mode of variability (mode 1) is characterized by substantial strengthening and spatial expansion of the jet core. Although there is a northward shift of the core away from the primary moisture source (Gulf of Mexico), the meridional expansion of the LLJ keeps the jet tied to the Gulf of Mexico. The enhanced strength of the jet core should lead to stronger low-level convergence in the jet-exit region, and thus precipitation (as shown later in Figure 12). An
inspection of PC1 shows substantial intraseasonal variability, with the PC switching sign in 18 of the 24 analyzed summers. PC1 is most negative in June 1988 and strongly positive in June-July 1993, coincident with severe drought and floods over the central United States in those summers.

Mode 2 represents a significantly northward shifted LLJ; much more than in mode 1. The negative values over the northern Gulf of Mexico along with anomaly-core location at 40-45°N, effectively isolates the LLJ from the Gulf moisture source. The PC2 distribution shows this mode to be in a positive phase during the 1988 drought, with the June PC value being the most positive. There is more intraseasonal variability in PC 2 as evidenced by sign changes in 21 of the 24 summers analyzed.

Mode 3 shows collocated strengthening of the climatological LLJ along with reduced meridional flow over the central/northern Great Plains, i.e., a meridional dipole structure. Strengthening (weakening) of the climatological LLJ is associated with floods (droughts) in the central U.S. due to enhanced (suppressed) moisture flux convergence. While the positive phase would have a slightly reduced northward moisture flux due to the climatology-opposing meridional winds over the eastern two-thirds of the Gulf of Mexico, the enhanced jet speed will lead to greater moisture flux convergence at the jet exit region in the central plains. The enhanced northward flux of moisture over the western portion of the Gulf of Mexico also makes an in-phase contribution. Note, the PC3 distribution indicates that mode 3 was not notably anomalous during the 1988 and 1993 summers, indicating a modest role for this mode of GPLLJ variability in these two prominent recent hydroclimate episodes.\(^7\)

\(^7\) All 3 PC’s were positive during July 1993.

\(b. \text{ Sensitivity to time period}\)
The analysis was repeated on the longer (40 + years) ERA40 data set (1958-2001) to ascertain the impact of record length on modal structures. The coarser resolution of ERA-40 data vis-à-vis NARR data was not considered too limiting a factor in this intercomparison. Figure 11 shows the EOF 2 pattern from ERA40 data analysis (left panel) in a similar manner to the left panels of figure 10. While there are some amplitude differences when compared to NARR’s EOF 2 (cf fig. 10), the two patterns are generally quite similar. The principal component of both EOF2s is regressed on 200 hPa heights. The NARR PC regressions on NARR heights are in the top panel while the ERA-40 ones are in the bottom-right panel. Again the differences are small and likely related to the different periods of regression. The large anticyclone over the north central U.S. in both regression patterns is especially noteworthy, given its prominence in central U.S. drought events (Bell and Janowiak 1995; Mo et al. 1997).

\(c.\) Precipitation regressions

Figure 12 shows the NARR PC regressions on NARR precipitation, which is close to the observed precipitation in view of successful precipitation assimilation in NARR. The EOF 1 regression is very similar to the GPLLJ index regression on precipitation (figure 7b); not surprising, given the strong correlation between PC1 and the GPLLJ index (0.86). The precipitation pattern linked with PC2 (middle panel) is more focused over the Gulf coast states and eastern U.S. seaboard. Unlike PC1 regressions, PC2 regressions exhibit a meridional dipole structure between the GPLLJ entrance and exit regions. PC2’s correlation with the GPLLJ index is \(-0.15\). The bottom panel displays the PC3 regressions, which show diminished precipitation over the south central U.S., and Mexico, and the Gulf of Mexico, and modest amplitude positive anomalies over the Great Plains. PC3 is correlated at 0.46 with the GPLLJ index. Of the three, only this mode has the potential to influence Mexican rainfall. Clearly, meridional wind
divergence \((\partial v/\partial y)\) alone cannot account for the negative precipitation anomalies along Mexico’s Gulf Coast, given the considerable similarity in EOF 1 and EOF 3 meridional wind anomalies in that region; EOF 1 regressions do not include this negative precipitation feature.

7. Discussion & Concluding Remarks

This study has sought to refine the characterization of the low-level circulation feature that transports vast amounts of moisture from the Gulf of Mexico into the continental interior during the summer months: the Great Plains Low-Level Jet. Much has been written about the GPLLLJ, especially, its remarkable diurnal variability, which includes a nocturnal maximum. The low-level jet is however more than a supplier of moisture to the Great Plains: the jet’s strength, shear, and related divergent circulations influence the timing, location, and intensity of precipitation in the continental interior (Stensrud 1996).

Unlike most studies of the jet, which focus on its mesoscale structure and dynamics, the present study seeks to characterize the jet’s structure and hydroclimate impacts in monthly-averaged circulation and precipitation datasets. Jet studies with monthly data would have been considered heretical up until a few decades ago, when spatially and temporally sparse observations would either be unable to represent many features of this vertically shallow and meridionally narrow jet; or if they did, the jet structure stood a reasonable chance of getting diluted, or even wiped out, upon monthly averaging of sparse observations; compromising any subsequent analysis.

The present analysis of GPLLJ structure, variability, and hydroclimate impacts in monthly averaged data sets became feasible only because of the recent availability of a high resolution (32 Km horizontal resolution, 25 hPa PBL resolution, 3-hourly) precipitation-assimilating regional
reanalyses over North America (NARR). The goal of this study was to uncover the monthly variability structure of the GPLLJ in NARR (and ERA-40) data and investigate the large-scale circulation context and origin of GPLLJ variability. The principal findings are:

- Diurnal range of the jet in the 3-hourly monthly NARR climatology shows a latitude dependence: For instance, the nighttime speed is 2.5 times the daytime value at 30°N, and only 1.67 at 25°N.

- Interannual variability of the GPLLJ can be reasonably represented by the areal average of the 900 hPa meridional wind anomalies in the 102°W-97°W and 25°N-35°N longitude-latitude box; defining the GPLLJ index.

- Jet index shows both intraseasonal and interannual variability. The NARR and ERA-40 indices are correlated at 0.97 in the 23-year overlapping analysis period. Notable index fluctuations include low (high) values in 1988 (1993); the drought and flood years over the central United States. The July index is correlated with the Great Plains precipitation index of Ruiz-Barradas and Nigam at 0.71.

- GPLLJ index regression as on July sea-level pressure and 200 hPa geopotential show a coherent large-scale wave pattern over the Pacific/North American region and also the mid-latitude Atlantic basin; indicating influence of basin-scale teleconnection patterns on GPLLJ variability (and ensuing hydroclimate impacts).

- Index regressions on SST and vertically averaged diabatic heating indicate a role for the tropics in generation of GPLLJ variability. The tropical influence is, perhaps, strongest in the summer following the ENSO mature phase.

- The recurrent modes of GPLLJ variability, embedded in the jet index, consist of jet-core strengthening and zonal/meridional expansion (PC1 explains 38% of the variance);
meridional jet-core shift (PC2, 23%); and in-place jet speed modulation with zonal/meridional compensation (PC3, 12%). The first and to an extent the second, mode is strongly linked with the 1988 drought and 1993 flood year jet anomalies. The GPLLJ index is well correlated with PC1 (0.86) and PC3 (0.46).

Focusing on monthly time scales and basin/continental scale circulation features has provided some insight into the origin of Great Plains low-level jet variability. The dynamical and thermodynamical interactions generating the summertime teleconnection patterns and ensuing jet modulation is the subject of ongoing analysis, predicated on lead/lag linkages in pentad time-scale circulation and precipitation data sets.
Acknowledgments

Alfredo Ruiz-Barradas, Chi-Fan Shih (NCAR), NCAR Scientific Computing Division.
References


Uccellini, L. W. and D. R. Johnson, 1979: The coupling of upper and lower tropospheric jet


Figure Captions

Figure 1. Longitude-height cross section of the seasonal evolution of the Great Plains Low-Level Jet as reflected in the meridional wind at 25° N (left column) and 30° N (right column) in the North American Regional Reanalysis at approximately .3° x .3° horizontal and 25 hPa vertical resolution. Contours > 5 m s⁻¹ are shaded. Topography is blocked out.

Figure 2. Longitude-height cross section of July diurnal evolution of the Great Plains Low-Level Jet as reflected in the meridional wind (solid) and temperature at (dashed) 25° N (left column) and 30° N (right column) for 4PM LT and 7 AM LT in the North American Regional Reanalysis. Contour interval is 1 m s⁻¹ and 2°k. Contours > 5 m s⁻¹ are shaded. Horizontal and vertical resolution is the same as fig. 1.

Figure 3. Seasonal evolution of the NARR 1000-700 hPa integrated meridional water vapor flux. Contour interval is 25 kg m⁻¹ s⁻¹ and values in excess of 75 kg m⁻¹ s⁻¹ are shaded. Horizontal resolution is the same as fig. 1.

Figure 4. Seasonal evolution of the diurnal amplitude and phase of the NARR 1000-700 hPa integrated meridional water vapor flux. Units are kg m⁻¹ s⁻¹. Direction of the arrow determines time of maximum amplitude. Arrow length denotes magnitude. Horizontal resolution is the same as fig. 1.

Figure 5. Area averaged (102-97°W, 25-35°N) meridional wind profile for the warm season months of May-August in the North American Regional Reanalysis. For July the ERA-40 reanalysis is included for comparison. The vertical resolution in NARR is 25 hPa and ERA-40 is 75 hPa. Units are m s⁻¹.

Figure 6. GPLLJ index anomalies during the warm season (May-July) in (top 2 panels) ERA-40 and in (bottom panel) NARR. Monthly values are shown using a triangle while the smoothed index obtained from a 1-2-1 averaging of the seasonal mean anomalies is displayed using solid lines. Horizontal dashed lines mark the plus minus 1 standard deviation range in each panel.

Figure 7. July regressions of the GPLLJ index (1979-2001) on NARR 900 hPa wind (a) and precipitation (b), ERA-40 200 hPa geopotential height (c), precipitation (d), and sea level pressure (e). Contour interval for: wind is 0.2 m s⁻¹, height is 5 m. Precipitation and SLP contours are 0.2 mm day⁻¹ and 0.2 hPa respectively. In all panels the positive values are shaded. The rectangular box outlines the area defined by the GPLLJ index.

Figure 8. Regression of the NAO index on 200 hPa height (top panel) in ERA40 and 900 hPa meridional winds (middle panel) and precipitation (bottom panel) in NARR. The contour interval in the top panel is 5 m while in the middle and lower panels it is 0.2 m s⁻¹ and 0.2 mm day⁻¹ respectively. Positive values are shaded. The rectangular box outlines the area defined by the GPLLJ index.
**Figure 9.** July regressions of the nocturnal GPLLJ index on 1000-200 hPa average diabatic heating (top panel) and Hadley SST (bottom panel). Diabatic heating contours are 0.1 k day$^{-1}$ while SST’s are contoured at 0.1 k. Dark (light) shading denotes positive (negative) values. The rectangular box outlines the area defined by the GPLLJ index.

**Figure 10.** 900 hPa meridional wind climatology for MJJ (shaded) and the first three EOF modes (contours) for MJJ in the left column. Meridional wind climatology values in excess of 4 m s$^{-1}$ are shaded at 1 m s$^{-1}$ intervals. The contour interval for the EOF spatial patterns is 0.2 m s$^{-1}$. MJJ principal component time series associated with each mode is displayed in the right column with percentages of explained variance of each mode.

**Figure 11.** EOF 2 (left panel; contoured) from principal component analysis and MJJ climatology (shaded; same as in fig. 10) of ERA-40 900 hPa meridional winds, and PC2 regression on 200 hPa height in both NARR (upper right) and ERA40 (lower right). The EOF contour interval is 0.2 m s$^{-1}$ and the 200 hPa height regressions are contoured at 5 m. The NARR regression is over the 1979-2001 time period while the ERA40 one is over 1958-2001. The rectangular box outlines the area defined by the GPLLJ index.

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