Observed trends in the Great Plains low-level jet and associated precipitation changes in relation to recent droughts

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[1] Recent drought over the Great Plains has had significant impacts on agriculture and the economy, highlighting the need for better understanding of any ongoing changes in the regional hydroclimate. Trends in the Great Plains low-level jet (GPLLJ) during the months April–June and associated precipitation are analyzed using the North American Regional Reanalysis (NARR) for the period 1979–2012. Linear trends computed for meridional winds and precipitation intensity, frequency, and total across the Great Plains show that (1) the GPLLJ has strengthened and expanded northward and (2) precipitation has decreased substantially in the Southern Plains while increasing in the Northern Plains. Particularly in May, the rainy season in the Oklahoma-Texas region, precipitation has migrated northward in correspondence to the shifted northern edge of the GPLLJ, leading to near 50% declines in precipitation since 1979. These observed changes are discussed in the context of recent droughts and projected climate for the region. **Citation:** Barandiaran, D., S.-Y. Wang, and K. Hilburn (2013), Observed trends in the Great Plains low-level jet and associated precipitation changes in relation to recent droughts, *Geophys. Res. Lett.*, *40*, 6247–6251, doi:10.1002/2013GL058296.

1. Introduction

[2] In the Midwest and Great Plains of the United States, agricultural production relies heavily on spring and summer precipitations, and variability of this water resource has profound impacts on farms and ecosystems alike. Extreme weather and climate events such as the floods of 1993 and 2008 or the droughts of 1988 and 2011–2012 led to profound hardship and economic disruption for the region [*Basara et al.*, 2013]. In addition to known extreme events, anecdotal evidence suggests that the seasonal precipitation in the Northern Plains (Nebraska, South/North Dakota), which historically has peaked in summer, is shifting to a regime similar to that of southern states (Oklahoma and Texas), which usually receive the most rain in late spring (B. Oglesby, personal communication, 2013). Thus, it is crucial to understand the driving forces behind such weather/climate extremes under changing climate patterns of the Great Plains.

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[3] One of the atmospheric circulation systems closely connected to the region's seasonal precipitation is the Great Plains low-level jet (GPLLJ), which is primarily a transient pattern of nocturnal strong winds just above the surface (i.e., below ~1000 m. above ground level) [*Stensrud*, 1996]. The GPLLJ transports water vapor from the Gulf of Mexico (GOM) and provides low-level moisture convergence at its northern edges, facilitating the formation of convective precipitation [*Higgins et al.*, 1997]. There have been numerous studies that outline the synoptic climatology [*Mitchell et al.*, 1995; *Wang and Chen*, 2009], interannual variability [*Weaver and Nigam*, 2008], and possible future changes of the GPLLJ [*Cook et al.*, 2008].

[4] Here we present findings on observed changes in the GPLLJ and concurrent changes in seasonal precipitation characteristics. We use the North American Regional Reanalysis (NARR) [*Mesinger et al.*, 2006] both for wind and precipitation data. NARR uses an assimilation scheme that incorporates rain gauge data and has been shown to adequately reproduce precipitation over the contiguous U.S. [*Bukovsky and Karoly*, 2007]. NARR was specifically chosen because of its high spatial (~32 km) and temporal (3 h) resolutions, which therefore resolves the GPLLJ and associated precipitation in greater detail. Since our analysis focuses on trends we compared NARR with the daily precipitation reanalysis of *Higgins et al.* [2000] and found no significant trend in the difference between data sets, so we assume that any model bias present in NARR precipitation is consistent and does not introduce any spurious trend in our analysis.

2. The Spring Rainy Season

[5] Over the Central U.S., warm season precipitation migrates from the southern Great Plains in spring to the Upper Midwest in summer. Both rainfall and convective storm activity reach their maximum in May and June in the Great Plains forming a precipitation center over eastern Oklahoma and northeastern Texas [*Wang and Chen*, 2009]. This rainfall maximum is depicted in Figure 1a by the second leading empirical orthogonal function (EOF) of monthly long-term mean precipitation. The corresponding principal component (PC) time series in Figure 1b reveals elevated seasonal precipitation from April through June (AMJ), peaking in May. However, over the past three decades the amount of spring precipitation in the region has declined. Figure 1c shows time series of pentad (5 day) mean precipitation averaged within the Oklahoma-Texas region (outlined in Figure 1a) for the period 1979–1995 (red) versus 1996–2012 (blue), with the percent difference between the two periods (yellow line). There is a clear reduction in AMJ rainfall, particularly the entire month of May during which deficits of as much as 50% are observed. Such a reduction

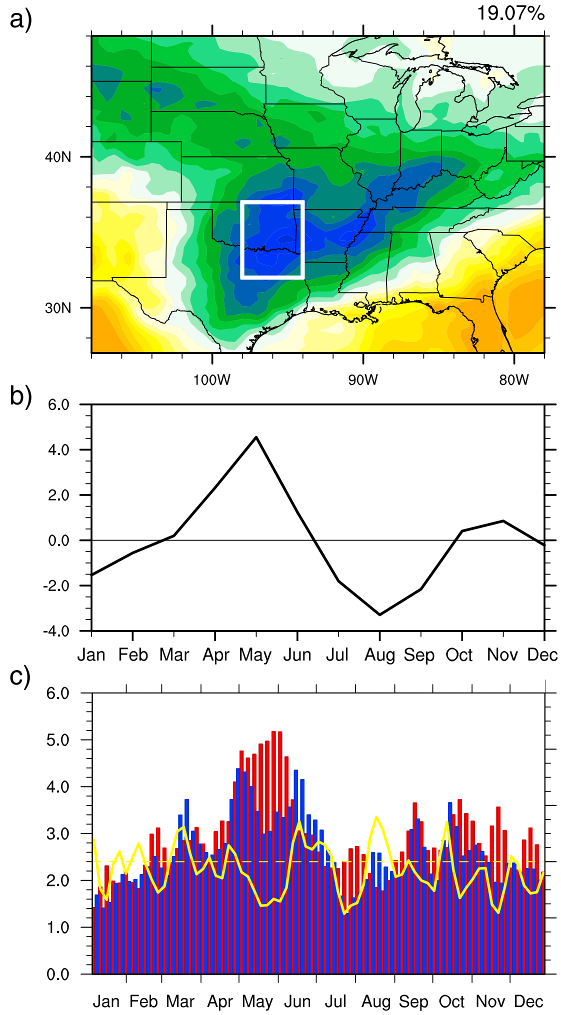

Figure 1. (a) EOF 2 of precipitation climatology for Central United States. White box highlights center of action and is used for the calculations for Figure 1c. (b) PC2 of precipitation climatology for Central U.S., showing the springtime peak of rainfall for the region. (c) Climatology of average pentad precipitation within the box in Figure 1a. Red bars are for the period 1979–1995; blue bars are for the period 1996–2012. Yellow line indicates percent difference between the two time periods.

in rainfall signifies the decline of a vital water source during the rainy season in the Oklahoma-Texas region.

[6] The association between the GPLLJ and daily rainfall systems is illustrated in Figure 2, i.e., Hovmöller diagrams of the 3-hourly precipitation and meridional wind (v component of wind) speed at 925 mb (the core level of the GPLLJ), averaged over the latitude range from the box in Figure 1a, and help to depict the daily evolution of weather. We present four cases: two are wet years (1987 and 1992) and two are dry years (2010 and 2012). During the wet years the strength of the GPLLJ is much less than during dry years, and the largest concentration of rainfall occurs in late May. In contrast, during dry years the month of May is noticeably drier, and the GPLLJ is much stronger and more frequent throughout AMJ. Also in these cases, dry spells are almost always accompanied by episodes of a strong GPLLJ.

[7] There is an apparent inverse relationship between the general strength of the GPLLJ and the amount of rain in this region during spring. Such a relationship has been documented in previous works [*Higgins et al.*, 1997; *Weaver and Nigam*, 2008] and reflects the fact that in order to provide the appropriate moisture convergence the GPLLJ must have its northern edge right over the Oklahoma-Texas area, without overshooting the region.

3. Long-Term Changes in the Spring Rainy Season

[8] *Cook et al.* [2008] have found that increased greenhouse gases would modify and eventually increase the strength of the GPLLJ. *Weaver and Nigam* [2008] found a noticeable intensification of the springtime GPLLJ up to year 2001 and noted the relationship between the strength of the GPLLJ and the distribution of precipitation in the Midwest. However, neither study established a link of the springtime GPLLJ tendency with increased dryness in the Oklahoma-Texas region. Thus, we next examine the extent to which the GPLLJ has changed and how this corresponds to the precipitation decrease and recent droughts in the region.

[9] Focusing on AMJ, Figure 3 shows a series of latitude time Hovmöller diagrams to depict the 1979–2012 change of the GPLLJ for each month. First, Figure 3a (leftmost column) depicts the climatological precipitation overlaid with 925 mb wind vectors for geographical reference. The white box in Figure 3a indicates the subregion over which averages were calculated in subsequent panels. In Figures 3b–3e, each panel presents a different variable averaged over the subregion. To construct these plots the trend for all latitudes is calculated using linear least squares regression for 6-hourly 925 mb v wind strength (Figure 3b), average precipitation intensity (Figure 3c), monthly frequency of rain (Figure 3d), and monthly total precipitation (Figure 3e). Rainfall frequency is defined as the number of 6-hourly time steps per month in which accumulated precipitation exceeds 1 mm. Latitudes in which the regression coefficient is significant at 95% confidence are indicated along the y axis. Note that these diagrams are linear trends added on the long-term mean, similar to a smoothed version of the monthly mean values plotted over time.

[10] For all 3 months of AMJ there is an apparent increase in the strength of v wind for the southern portion of the domain, particularly between 30°N and 35°N including the GOM (i.e., upstream of the GPLLJ). There is also a northward migration of the maximum gradient of v wind speed and the resultant convergence at the exit region of the GPLLJ. Correspondingly, the changes in total precipitation (Figure 3e) reveal a northward migration especially in May; in April there is a positive trend in precipitation from 32°N to 45°N with the greatest increases at ~35°N, suggesting a shift in the position of the spring center shown in Figure 1a. Accompanying this northward migration of precipitation is a concurrent increase and migration in rainfall frequencies and overall precipitation intensity (Figures 3c and 3d), particularly in May.

[11] Perhaps the most profound implication of these migrating precipitation characteristics is the drying trend in the Oklahoma-Texas region. In May, the precipitation reduction is directly linked to the decreasing frequency of rain events and reduced rainfall intensity, along with the strengthened GPLLJ. In June the greatest change in precipitation is found south of 34°N showing a negative trend in the frequency of precipitation. North of this latitude trends for total precipitation approach zero, but there is a

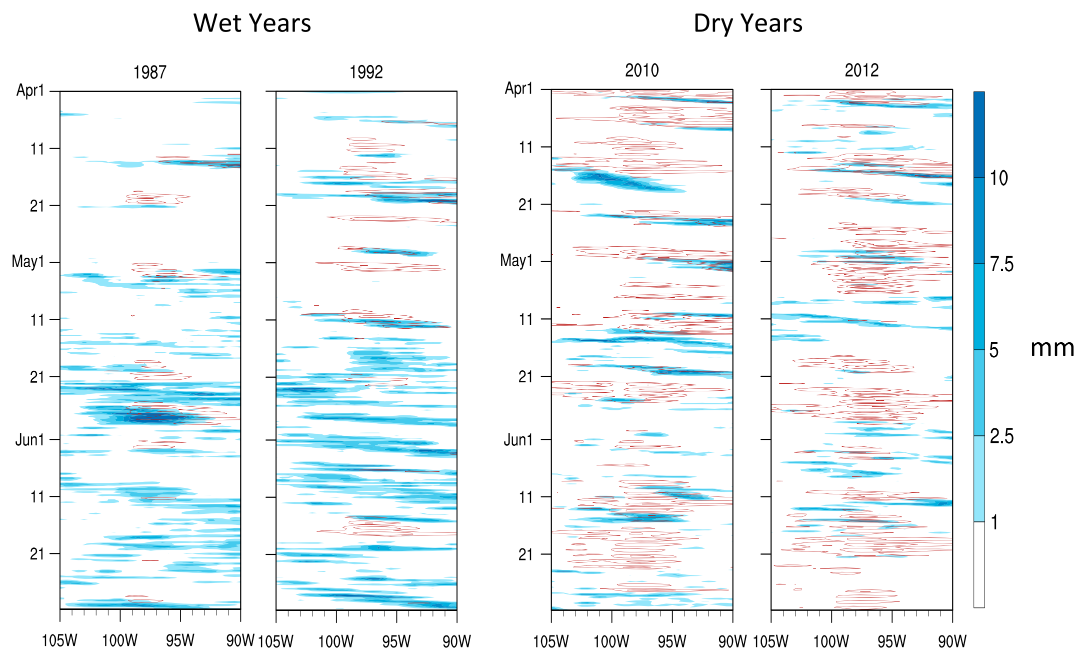

Figure 2. Longitude time Hovmöller diagrams, averaged over latitudes 32°N to 37°N. Contour lines show 925mb *v* wind magnitude (i.e., location of GPLLJ core), 10–30 m/s in 5 m/s intervals.

narrow band from 36°N to 40°N in which precipitation intensity has increased, yet precipitation frequency has decreased. This increase in precipitation intensity is collocated with a slight increase in total precipitation, suggesting less frequent but stronger storms. These changes in precipitation characteristics are apparently linked with the change in the GPLLJ. As the jet intensifies and expands northward, its migrating northern boundary (or *v* wind gradient) enhances precipitation activity to the north due to increased convergence but weakens it in the south due to increased divergence.

[12] These results point to the changing GPLLJ dynamics in the spring rainy season and raise questions about possible changes in moisture supply. We therefore look at trends in water vapor over the GOM, i.e., the GPLLJ moisture source region, measured by the Special Sensor Microwave Imager (SSM/I + SSMIS), which provide robust retrievals of water vapor for climate monitoring [*Wentz and Schabel*, 2000; *Mears et al.*, 2007]. The polar-orbiting SSM/I sensors provide as many as two observations per day at a particular location. We used the Version-7 data [*Wentz*, 2013], which are available for the time period 1987–2013 and are at ~25 km spatial resolution.

[13] Figure 4 shows the trend in total precipitable water from SSM/I for AMJ. The trends measured by SSM/I alternate from negative in April to positive in June, but these changes are small and insignificant for all but a few isolated areas. Precipitable water trends over the GOM from NARR disagree with SSM/I however and show significant reductions in all 3 months (not shown). Given the direct impact that GOM moisture plays on weather systems across the Central United States, resolving this apparent discrepancy in summertime precipitable water trends between NARR and SSM/I is an important question but beyond the scope of this article. Regardless, there is not a clear positive trend in any of the months of interest, when contrasted with the findings in *Dirmeyer and Kinter* [2010], which showed that changes in source moisture and rainfall over the Great Plains are positively correlated.

[14] While there is uncertainty in GOM vapor trends, the increase in Central/Northern Plains rainfall is most likely explained by a more favorable dynamical environment for thunderstorm development provided by low-level convergence in the GPLLJ exit region and upper level lifting associated with the jet stream; both of which have intensified and migrated northward [see also *Wang et al.*, 2013]. It should be noted that a reduction in source moisture of the GPLLJ might be partially compensated by evaporated irrigation water from agricultural activities [*DeAngelis et al.*, 2010]; such an explanation requires further analysis.

4. Summary and Discussion

[15] Analysis of NARR indicates notable increases in both the strength and northern extension of the GPLLJ for AMJ. There are concurrent changes in precipitation that vary by month but show common increases north of 40°N in the total amounts, frequency, and intensity. Meanwhile, substantial decreases in total precipitation are evident south of 40°N, with consistent reductions in both frequency and intensity of rainfall. In addition to the increased strength and extent of the GPLLJ, there has been a concurrent northward shift of the upper level jet stream, i.e., 200 mb *u* wind during May (not shown). The upper level jet stream provides synoptic support for the development and maintenance of thunderstorms, and its northward migration coupled with increased extent of the GPLLJ helps maintain synoptic lift [*Wang et al.*, 2013], hence enhancing precipitation toward the Northern Plains. However, the intensification of extreme precipitation events seen in June is not accompanied by any changes in the upper jet (not shown) but appears to be closely tied to increased strength of the GPLLJ alone; this suggests a possible role of the increase in source moisture over the GOM in June. A modest decrease in moisture from the source region is found in April and May, but these changes do not have a consistent impact on precipitation further

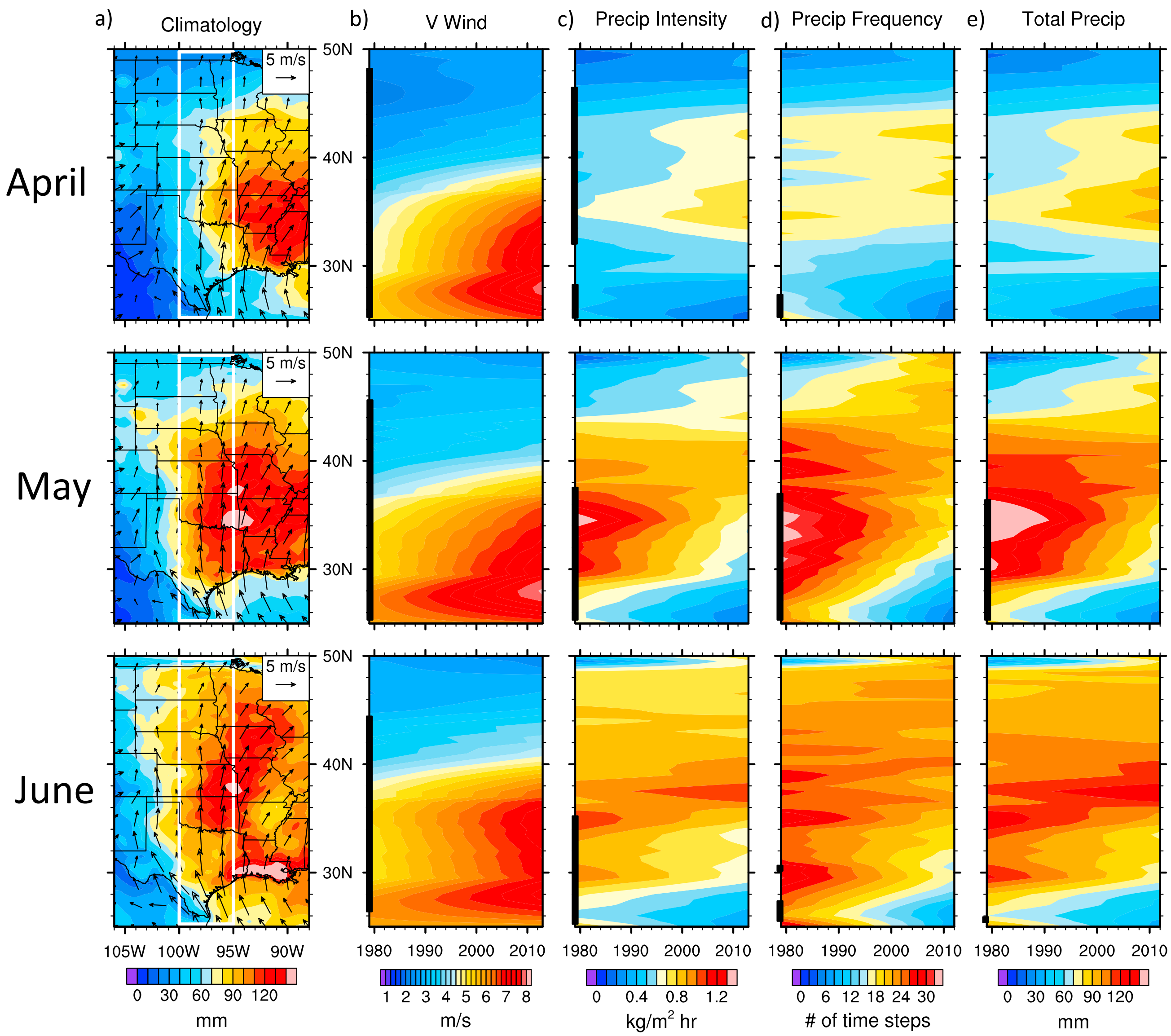

Figure 3. (a) Monthly climatology for precipitation (shaded) and 925mb wind field (vectors) and latitude time Hovmöller trend plots for (b) 925mb *v* wind, (c) precipitation intensity, (d) precipitation frequency, and (e) monthly total precipitation, averaged along the longitude range indicated by the white boxes within monthly climatology plots. Data plotted consists of regressed linear trend added to climatological mean. Thick bars along latitude axis on trend plots indicate latitudes for which regression coefficients are statistically significant at 95% confidence.

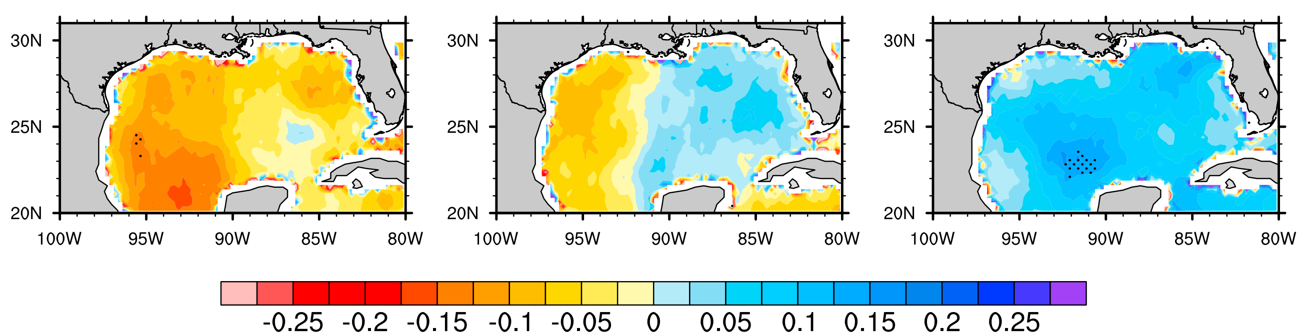

Figure 4. Linear regressions (1987–2012) of column-integrated water vapor over the Gulf of Mexico from SSM/I. Units are mm/year. Stippling indicates statistical significance at 95% confidence.

inland. The ambiguity of these contrasting observations is further compounded by the fact that model and satellite data sets sometimes disagree on the sign of the vapor trend over the GOM. Thus, the observed changes in the precipitation characteristics (i.e., amount, frequency, and intensity) appear to be predominantly controlled by the observed change in atmospheric circulations, especially the GPLLJ.

[16] The trends in the GPLLJ and precipitation reported here are supportive of previous findings in observations as well as future projections based on modeling studies. *Cook et al*. [2008] predicted that increases in greenhouse gases would result in an intensification of the GPLLJ, higher rainfall in the northern Great Plains, and reduced precipitation in the southern Great Plains. *Wang et al*. [2013] reported that the coupling between the GPLLJ and upper level trough system has intensified during AMJ since 1979. In contrast, previous studies found evidence of the impacts of decadal climate oscillations in the Pacific and the Atlantic on the GPLLJ [*Weaver et al*., 2009; *Nigam et al*., 2011], as well as multidecadal influences on GPLLJ-related processes [*Weaver et al*., 2012]. With the limited temporal domain of NARR, decadal to multidecadal processes cannot be ruled out. Nonetheless, there is still the possibility that predicted changes in the GPLLJ and associated precipitation [*Cook et al*., 2008] are already underway.

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