ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **16**: 512–517 (2015)
Published online 28 July 2015 in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl.590

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The changing influence of El Niño on the Great Plains low-level jet

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Received: 13 February 2015
Revised: 12 May 2015
Accepted: 28 May 2015

Abstract

This study finds that the El Niño influences on the summer Great Plains low-level jet (GPLLJ) are different for the Central Pacific (CP) and Eastern Pacific (EP) types during their decaying phases. While the CP El Niño induces negative sea level pressure anomalies over the Gulf of Mexico to drive anomalous northerly winds weakening the GPLLJ, the EP El Niño intensifies the GPLLJ by inducing anomalous surface air temperature gradient between the northeastern and southwestern United States. The recent emerging CP El Niño can weaken the GPLLJ to lead to a drier environment in the central United States.

Keywords: **CP El Niño; EP El Niño; GPLLJ**

1. Introduction

The Great Plains of the United States contributes more than 40% of the total agroeconomics in North America. The Great Plains low-level jet (GPLLJ) plays an important role in modulating the transport of heat and moisture from the Gulf of Mexico into the region during spring and summer. Several studies have attributed the 1988 drought and 1993 flood in the Mississippi Valley to the weakening and strengthening of the GPLLJ (Ting and Wang, 2006; Cook *et al.*, 2008). Variations in the strength of the GPLLJ and its associated moisture transport were also suggested to be a contributing factor for springtime tornado activity in the United States (Weaver *et al.*, 2012; Lee *et al.*, 2013). Therefore, understanding the climatic factors that modulate the strength of the GPLLJ is crucial for the hydroclimate and socioeconomics of North America.

Several large-scale factors play key roles in influencing the GPLLJ. The alternate warming and cooling of sloping terrain of the eastern Rocky Mountains are one of the factors that contribute to the persistence of the GPLLJ (Bonner and Paegle, 1970). The GPLLJ has also been considered to be a result of the westward extension of the North Atlantic subtropical high in the presence of monsoonal heating (Rodwell and Hoskins, 2001) and the blocking effect of the North American orography (Byerle and Paegle, 2003; Ting and Wang, 2006). Upper-level westerly jet streaks were suggested to be important to the development of the GPLLJ (Uccellini, 1980; Byerle and Paegle, 2003; Mo and Berbery, 2004). Model experiments have shown that sea surface temperature (SST) changes in the tropical North Atlantic play an important role in GPLLJ variations (Wang *et al.*, 2007; Wang *et al.*, 2008). Variations in the Pacific SST were also considered important in causing GPLLJ variability (e.g. Trenberth and Guillemot, 1996). El Niño events have been suggested to be capable of influencing the GPLLJ strength in their decaying phase (Weaver and Nigam, 2008). Idealized general circulation model (GCM) experiments further indicated that El Niño events favor a stronger GPLLJ (Weaver *et al.*, 2009).

Recent studies have emphasized that there exist at least two types of El Niño (e.g. Larkin and Harrison, 2005; Kao and Yu, 2009): the conventional El Niño characterized by warm SST anomalies in the Eastern Pacific (EP) and the Central Pacific (CP) El Niño that develops mostly around the international dateline (Yu and Kao, 2007; Kao and Yu, 2009). These two types of El Niño have been shown to produce distinct impacts on the wintertime temperature and precipitation in the United States (Mo, 2010; Yu and Zou, 2013) and springtime streamflow in the Mississippi River (Liang *et al.*, 2014). Since El Niño has changed from the EP type to the CP type in recent decades (e.g. Larkin and Harrison, 2005; McPhaden *et al.*, 2011; Yu *et al.*, 2012b), the El Niño impacts on the central United States during spring/summer may have also changed via the modulation of the GPLLJ. In this study, we stratify the El Niño impacts on the GPLLJ according to its type.

2. Data and methods

The National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) reanalysis dataset (Kalnay *et al.*, 1996) is used for the analyses of monthly anomaly fields. The reanalysis product is available from 1948 to 2010 with a horizontal resolution of 2.5° longitude by 2.5° latitude. In the study, anomalies are defined as the deviation from the 1948 to 2010 climatology. Also used are the EP and CP ENSO indices, which were calculated from the National Oceanic and Atmospheric Administration (NOAA)'s Extended Reconstructed Sea Surface Temperature V3b dataset (Smith and Reynolds, 2003) using a regression-EOF (Empirical Orthogonal Functions) method (Kao and Yu, 2009). A total of 21 major El Niño events were identified during the analysis period based on the Ocean Niño Index (Trenberth and Stepaniak, 2001). The types of these El Niño events have been determined based on a 'consensus method' developed by Yu *et al.* (2012a), whose details are explained in the Appendix S1, Supporting Information.

3. Results

The GPLLJ is characterized by strong low-level southerly winds (maximum wind speed is about $8\,\mathrm{m\,s^{-1}}$) in the central United States during late spring/early summer (Ting and Wang, 2006; Cook *et al.*, 2008; Weaver and Nigam, 2008). Figure 1(a) shows the climatological values (1948–2010) of the May-June-July (MJJ) mean meridional winds at 925 hPa over the United States. The low-level jet can be identified as the maximum in wind speeds over the Great Plains of the United States, which also extends southward to northeastern Mexico. The GPLLJ is particularly prominent in the Texas, Oklahoma, and south Kansas region; its magnitude decreases toward the north. The deviations of the composited meridional winds from the climatology are found to be statistically significant for the two types of El Niño only during their decaying phases (Figure 1 (b) and (c)) at the 90% level using a two-tailed Student's *t*-test. The deviations during the developing phases do not pass the 90% level for the CP El Niño composite and only barely pass the test for the EP El Niño composite (Figure S1). In the rest of this study, we focus only on El Niño's impacts during its decaying phase. During the decaying phase of the EP El Niño, the strength of the GPLLJ increases by as much as $0.5\,\mathrm{m\,s^{-1}}$, which is about 6% of the climatological value. The strengthening of the GPLLJ is most obvious over Missouri and Arkansas, which is the northern portion of the GPLLJ. In contrast, the composite for the CP El Niño (Figure 1(b)) events shows a decrease in the meridional winds over the GPLLJ region. The decrease is particularly large over the southern portion of the GPLLJ, including Texas, Louisiana, and Arkansas. The strength of the GPLLJ weakens by about $0.5\,\mathrm{m\,s^{-1}}$. Figure 1 indicates that the conventional view of a strengthening effect of El Niño on the GPLLJ (e.g. Weaver *et al.*, 2009) is true only for the EP type of El Niño. A distinct and opposite effect is produced by the CP type of El Niño. We also found precipitation decreases (increases) when CP (EP) El Niño events occur (Figure S2), which corresponds to a weakening (strengthening) of the GPLLJ. To make sure the results are not dependent on the reanalysis products used, we repeated the wind analysis using the ERA-Interim reanalysis product (Dee *et al.*, 2011) and the precipitation analysis using an observation-based precipitation dataset [Parameter-elevation Relationships on Independent Slopes Model (PRISM), Daly *et al.*, 2008]. Similar results are found (not shown), which indicates that the features found here are robust across data products.

To understand why the two types of El Niño produce opposite influences on the strength of GPLLJ, we examined the large-scale circulation features over the United States during the MJJ season. Figure 2 shows the MJJ-mean sea level pressure (SLP) and 925-hPa wind anomalies composited for the two types of El Niño during their decaying phases. Associated with the CP El Niño (Figure 2(a)), significant negative SLP anomalies are found over the Gulf of Mexico and are accompanied by cyclonic wind anomalies. Northerly wind anomalies are produced in the GPLLJ region (indicated by a square box in the figure) to weaken the GPLLJ. A different SLP anomaly pattern is found in the composite for the EP El Niño (Figure 2(b)). The anomalies are characterized by a north–south dipole pattern over the United States, which would have induced zonal wind anomalies rather than meridional wind anomalies. Instead, we observed southerly wind anomalies in the region, indicating that the SLP anomaly dipole is not the mechanism to strengthen the GPLLJ. Additionally, the strongest meridional pressure gradients associated with this SLP anomaly pattern occur in regions that are far from the GPLLJ. Therefore, the SLP anomalies induced by the EP El Niño do not seem to explain its strengthening effect on the GPLLJ.

We find that the surface air temperature (SAT) anomaly pattern associated with the EP El Niño seems to be capable of explaining its strengthening effect on the GPLLJ better than the associated SLP anomaly pattern. As shown in Figure 3(b), negative SAT anomalies are observed to the west and southwest of the GPLLJ, while significant and positive SAT anomalies are observed to the north and northeast of the GPLLJ. The east–west dipole in the thermal structure results in a positive longitudinal temperature gradient ($\mathrm{d}T/\mathrm{d}x > 0$), which should induce a southerly jet anomaly according to the thermal wind balance. We use the thermal wind balance to calculate the vertical wind shear in the lower troposphere from the horizontal surface temperature gradient. The vertical wind shear is then used to estimate the 925-hPa (i.e. the GPLLJ level) wind anomalies from the composite surface wind anomalies. As shown in Figure 4, the estimated 925-hPa wind anomalies for the EP El Niño are similar to the composite 925-hPa wind anomalies over the central United States including the GPLLJ region. This analysis demonstrates that the strengthening of the GPLLJ at 925-hPa during the EP El Niño can be explained by the horizontal temperature gradient anomalies via the thermal wind balance. No such correspondence is found for the CP El Niño (not shown). The temperature anomaly pattern shown in Figure 3(b) is similar to that of typical EP El Niño impact on US

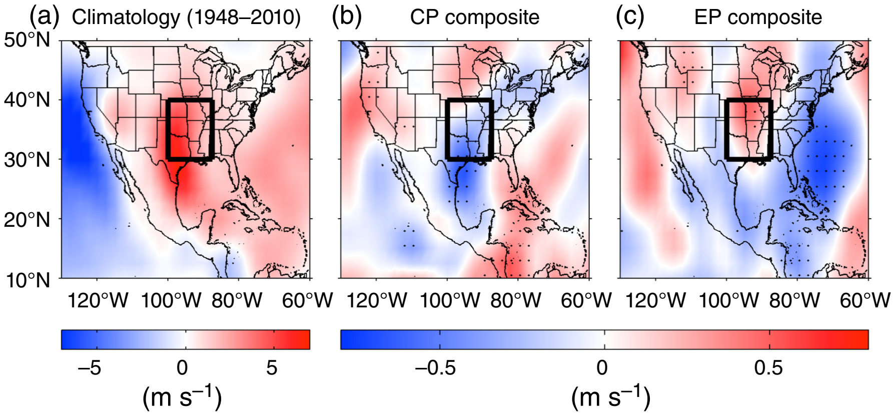

Figure 1. Meridional winds at 925 hPa during the May-June-July (MJJ) season: (a) the climatological values (1948–2010); (b) the anomalies composited from the 13 CP El Niño events during their decaying phase; and (c) the anomalies composited from the eight EP El Niño events during their decaying phase. Statistically significant deviations are stippled. Boxes in the panels indicate the GPLLJ region, which is bounded in latitude by 30° and 40°N and in longitude by 87° and 101°W.

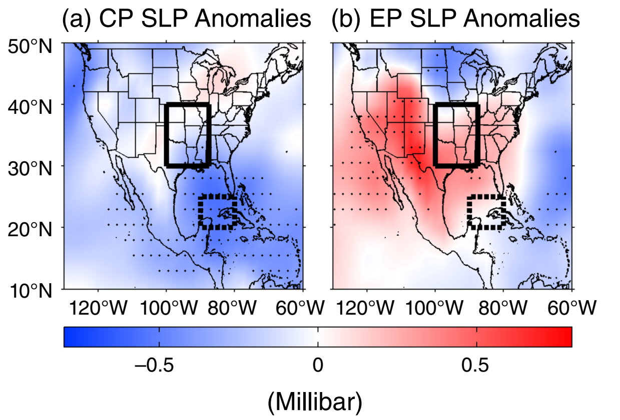

Figure 2. MJJ-mean sea level pressure anomalies composited for the (a) CP El Niño events and (b) the EP El Niño events during their decaying phases. The solid boxes are defined as in Figure 1. The dashed boxes are defined as the region bounded in latitude by 20° and 25°N and in longitude by 80° and 90 W. Statistically significant deviations are stippled.

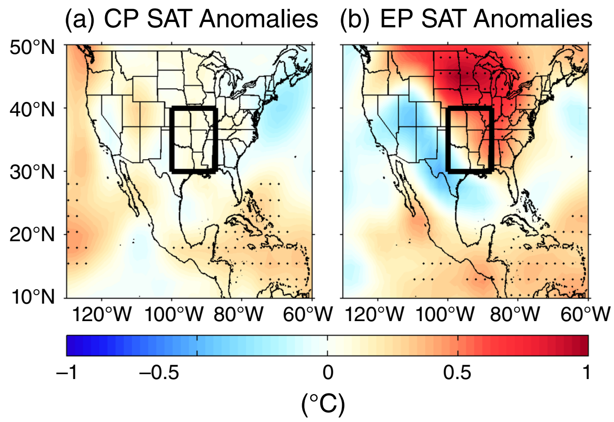

Figure 3. MJJ-mean surface air temperature anomalies composited for (a) the CP El Niño events and (b) the EP El Niño events during their decaying phases. The boxes are defined as in Figure 1. Statistically significant deviations are stippled.

winter temperature reported by Yu *et al.* (2012a). They suggested that this southwest-to-northeast anomaly pattern is a result of the Tropical-Northern Hemisphere (TNH) wavetrain excited by the EP El Niño. Land hydrological processes (e.g. Liang *et al.*, 2014) may be responsible for sustaining the temperature anomalies from the winter season to the summer season. Local water management practices (such as irrigation) could affect the surface temperature pattern via modulations in the surface energy budget (Sacks *et al.*, 2009; Lo and Famiglietti, 2013) and result in changes in the strength of the low-level jet (Huber *et al.*, 2014). The induced southerly wind anomalies may also play an important role in contributing to the warming via moisture and heat transport from the southern part of the Great Plains and the Gulf of Mexico. Further analyses are required to better understand their impacts on sustained surface temperature anomalies.

In contrast, no significant surface temperature anomalies can be identified over the United States during the CP El Niño events (Figure 3 (a)), which indicates that the CP El Niño impacts on the GPLLJ strength cannot be explained by the same thermal wind balance argument. The negative SLP anomalies identified over the Gulf of Mexico during CP El Niño events (Figure 2(a)) are found to be a prolonged dynamic response of the United States to the CP SST anomalies. In Figure 5, we performed a lag correlation analysis between the wintertime (December-January-February) EP and CP ENSO indices and the SLP anomalies through winter to the following summer over the Gulf of Mexico [region indicated by the dashed square box in Figure 2 (a) and (b)]. As shown in Figure 5, both the CP and EP ENSO indices have negative correlation coefficients (between −0.6 and −0.5) with the Gulf of Mexico SLP anomalies during the winter, and the negative correlations weaken in the following seasons. The decaying correlation indicates that the ENSO influences on the Gulf of Mexico SLPs decreases during the decaying phase of El Niño events. However, the correlation coefficient decreases more slowly for the CP ENSO index (blue line) than for the EP El Niño index (red line). In MJJ, the correlation coefficient with the CP El Niño is

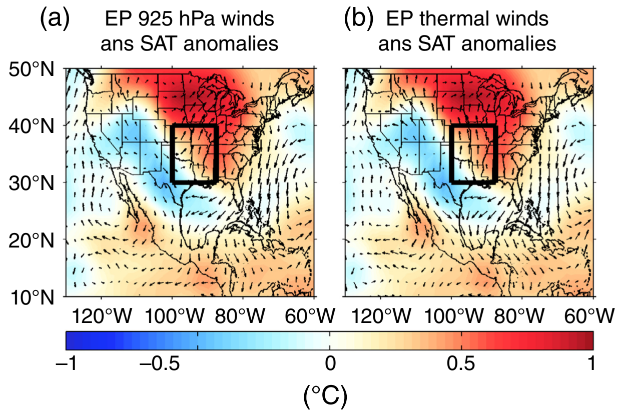

Figure 4. (a) MJJ-mean wind anomalies (vector) at 925 hPa composited from the decaying phase of the EP El Niño. (b) MJJ-mean wind anomalies (vector) at 925 hPa estimated from the thermal wind balance during the decaying phase of the EP El Niño. Composite MJJ-mean surface air temperature (SAT) anomalies are shown as color shadings in both panels. The boxes are defined as in Figure 1.

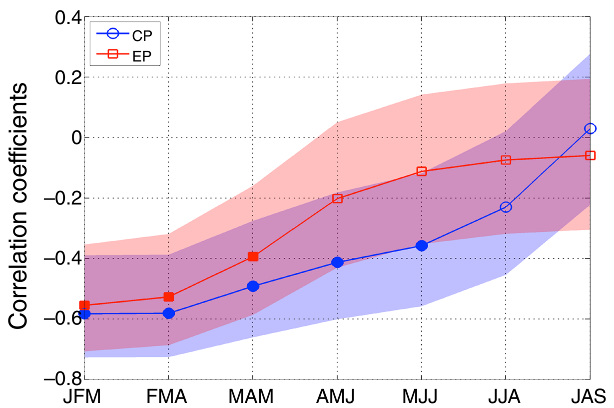

Figure 5. Correlation coefficients between the CP and EP ENSO indices and the SLP anomalies averaged in a region between 20°–25°N and 80°–90°W [i.e. the dashed square boxes in Figure 2 (a) and (b)]. Filled symbols indicate statistically significant points with p-value less than 0.05. The shaded area indicates 95% confidence interval for coefficients.

about −0.35. This value is still statistically significant at the 95% level, while the correlation with the EP ENSO index has already plunged to about −0.1. This analysis suggests that the winter CP El Niño SST anomalies have a more prolonged impact on the SLP fields over the Gulf of Mexico than that for the EP El Niño.

To confirm further the opposite influence produced by the two types of El Niño on the strength of the GPLLJ, we examined the strength during the MJJ season for each of the 21 El Niño events after 1950. The GPLLJ strength is quantified by a GPLLJ index, which was defined as the meridional winds averaged in the box shown in Figure 1 (a). Figure 6 shows the deviation of this index from its climatological value for all the El Niño events analyzed in this study. Ten of the 13 (77%) CP El Niño events show a weakening of the GPLLJ, while 6 of the 8 (75%) EP El Niño events show a strengthening of the GPLLJ. After the

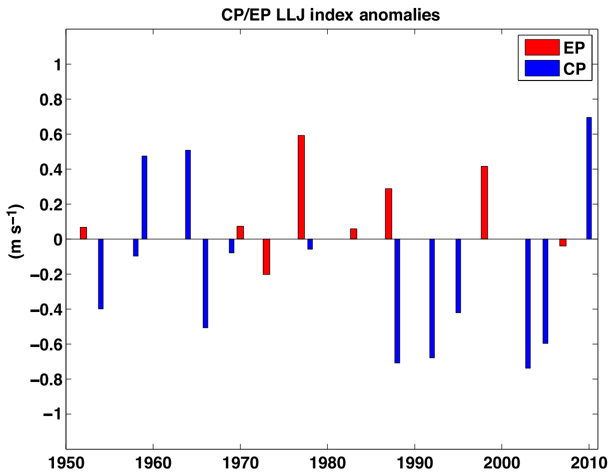

Figure 6. Values of the GPLLJ index (see text for its definition) calculated for the 21 major El Niño events after 1950. The blue bars indicate CP El Niño events, and the red bars indicate EP El Niño events.

late 1980s, it is obvious that the frequent occurrence of CP El Niño events leads to a weakening of the GPLLJ, except during the 2009–2010 El Niño event. It should be noted that three CP El Niño events (1958–1959, 1963–1964, and 2009–2010) and two EP El Niño (1972–1973 and 2006–2007) produced impacts on the GPLLJ that are opposite from those suggested by the composite analyses. The possible causes for these exceptional events are discussed in the Appendix S1.

4. Discussion

This study provides evidence to show that the two types of El Niño can produce opposite impacts during their decaying phases on the strength of the GPLLJ during late spring and early summer. The finding has several implications for understanding, predicting, and projecting the US summer climate. In 1988, a severe drought damaged the agroeconomics in the central United States and cost approximately \$40.0 (61.6, adjusted to 2002 value) billion dollars (Ross and Lott, 2003). The northward displacement of the jet stream and positive upper-level height anomalies above the Great Plains were considered to be causes for the drought (Basara *et al.*, 2013). We are not aware of any studies that have attributed this drought event to El Niño. According to the ‘consensus El Niño type’ identified by Yu *et al.* (2012a), 1988 was the decaying period of the 1987–1988 CP El Niño. Our results indicate that this CP El Niño event had the potential to contribute to the reduction in strength of the MJJ GPLLJ, which may have weakened the moisture transport from the Gulf of Mexico into the Great Plains. This may have been a contributing factor for the severe drought in 1988.

Recent studies have indicated that the GPLLJ has become stronger and migrated northward since 1979, leading to an increasing trend in the precipitation in the central and northern Great Plains but a significant reduction in rainfall in the Southern Plains (Barandiaran *et al.*, 2013). GCM simulation results have suggested that global warming may amplify the GPLLJ in the future mainly due to a westward extension of a stronger North Atlantic subtropical high (Cook *et al.*, 2008). This study suggests that the strengthening effect caused by global warming may be partially offset by the CP El Niño that has been suggested to occur more frequently in a warmer world (e.g. Yeh *et al.*, 2009; Kim and Yu, 2012).

The impacts of the CP El Niño SST anomalies on the Great Plains via SLP changes reported here imply that El Niño SST anomalies may become more useful in predicting summertime US climate as El Niño changes from the EP type to the CP type.

Acknowledgements

This research was supported by NOAA's MAPP Program (grant A11OAR4310102), NSF (grant AGS-1233542), NOAA Climate Program Office, and the base funding of NOAA/AOML. Dr Min-Hui Lo is supported by the grant of MOST 103-2111-M-002-006. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency.

Supporting information

The following supporting information is available:

Figure S1. Meridional winds at 925 hPa during the May-June-July (MJJ) season: (a) the climatological values (1948–2010); (b) the anomalies composited from the 13 CP El Niño events during their developing phase; and (c) the anomalies composited from the eight EP El Niño events during their developing phase. Statistically significant deviations are stippled. Boxes in the panels indicate the GPLLJ region, which is bounded in latitude by 30° and 40°N and in longitude by 87° and 101°W.

Figure S2. Precipitation anomalies druing May, June, and July composted for the CP El Niño events (upper panels) and the EP El Niño events (lower panels) in their decaying phases. Statistically significant deviations are stippled. The square box is defined as in Figure S1.

Figure S3. MJJ-mean SST anomalies averaged from (a) the three 'exceptional' CP El Niño events (1958–1959, 1963–1964, and 2009–2010) and (b) the two 'exceptional' EP El Niño events (1972–1973 and 2006–2007).

Figure S4. MJJ-mean SST anomalies averaged from (a) the 'normal' CP El Niño events (i.e. excluding the 1958–1959, 1963–1964, and 2009–2010 exceptional events) and (b) the 'normal' EP El Niño events (i.e. excluding the 1972–1973 and 2006–2007 exceptional events).

Appendix S1. El Niño indices and ENSO types, and potential causes for the irregularity of GPLLJ.

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