GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L23701, doi:10.1029/2005GL023759, 2005

Effects of atmospheric teleconnections on seasonal precipitation in mountainous regions of the southwestern U.S.: A case study in northern New Mexico

Huade Guan, Enrique R. Vivoni, and John L. Wilson

Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA

Received 8 June 2005; revised 7 September 2005; accepted 14 October 2005; published 1 December 2005.

[1] This study uses instrument records and geostatistical modeling to examine hydrologically important temporal and spatial patterns of seasonal precipitation associated with the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) in a mountainous region of northern New Mexico. PDO is the more dominant factor, compared to ENSO, with a larger influence on winter and spring precipitation (wetter for high PDO, drier for low PDO). Extreme ENSO effects are not significant during the high PDO years, but during low PDO years El Niño strongly dampens winter and spring precipitation anomalies. Elevation modulates ENSO and PDO effects on winter anomalies, but does not seem to for other seasons. For a wetter-than-normal winter, the anomalies are larger at higher elevations, and are positive. For a drier-than-normal winter, the anomalies are larger at lower elevations, and are negative. For neutral ENSO, summer precipitation is predictable but spatially variable, indicating different local climates. High-resolution mapping brings out hydrologically important patterns of precipitation anomalies that would otherwise be blurred by spatial averaging.

Citation: Guan, H., E. R. Vivoni, and J. L. Wilson (2005), Effects of atmospheric teleconnections on seasonal precipitation in mountainous regions of the southwestern U.S.: A case study in northern New Mexico, *Geophys. Res. Lett.*, *32*, L23701, doi:10.1029/2005GL023759.

1. Introduction

[2] In arid and semiarid regions, mountains provide a majority of the fresh water to surrounding alluvial basins. In the southwestern United States, a dramatic increase in population over the past decades challenges water management. The current situation calls for urgent study of mountain hydrology, especially its response to climate variability at an appropriate scale of interest. Improved estimates of precipitation distributions in mountains are critical, although difficult due to complex terrain and intra- and inter-annual variations [e.g., *Higgins and Shi*, 2000]. One portion of this variability is due to unpredictable atmospheric processes while another portion is associated with global atmospheric circulations coupled to periodic ocean conditions [e.g., *Ropelewski and Halpert*, 1986; *Gershunov and Barnett*, 1998].

[3] For the southwestern U.S., a relationship has been observed between the El Niño-Southern Oscillation (ENSO) and the amounts and variability of winter precipitation [e.g., *Andrade and Sellers*, 1988; *Sheppard et al.*, 2002]. Winter precipitation usually increases during El Niño (ENSO warm phase), and decreases during La Niña (ENSO cold phase). Recent studies suggest that the La Niña effect is not as strong as the El Niño control on winter precipitation [e.g., *Kunkel and Angel*, 1999; *Goodrich*, 2004]. These atmospheric teleconnections provide a potential tool for water management in the region [*Simpson and Colodner*, 1999]. For hydrologic purposes, it is appropriate to explore the predictive skill of atmospheric teleconnections for seasonal precipitation throughout the year, not just for the winter season. However, summer precipitation in the southwestern U.S. is usually not highly correlated to ENSO (or PDO) [*Andrade and Sellers*, 1988; *Adams and Comrie*, 1997; *Sheppard et al.*, 2002], although a few studies have observed minor correlations [e.g., *Barlow et al.*, 2001; *Castro et al.*, 2001].

[4] The ENSO teleconnection with winter precipitation is causally related to and modulated by the Pacific Decadal Oscillations (PDO) [*Gershunov and Barnett*, 1998; *Gutzler et al.*, 2002]. The teleconnection patterns (i.e. dry winter in La Niña, and wet winter in El Niño) are enhanced by a constructive relationship between ENSO and PDO (ENSO warm (cold) phase + high (low) PDO phase); and dampened by a destructive relation (ENSO warm (cold) phase + low (high) PDO phase). In prior studies using precipitation records, the PDO effect was considered as a secondary factor, serving to modulate ENSO-induced variability [*Gutzler et al.*, 2002]. Only recently [*Goodrich*, 2004] has an instrument based study considered PDO independently. In any event, it is difficult to study decadal oscillations using records that are limited in length. Some studies extend the record by using proxies, such as tree rings [e.g., *Gray et al.*, 2003]. Nevertheless, instrument studies of decadal oscillations, like *Gershunov and Barnett* [1998], *Gutzler et al.* [2002], and this study, retain scientific value despite their limited record length.

[5] Due to orographic effects, mountain precipitation amounts and variability can differ significantly from the surrounding valleys (where many rain gauges are placed). As a result, a bias may be introduced when using valley-clustered NCDC (National Climate Data Center) gauge data for studying atmospheric teleconnections in mountain regions [*Kunkel and Angel*, 1999]. For example, ENSO can affect local atmospheric circulation leading to variations in orographically-induced precipitation as a function of ENSO phase [*Dettinger et al.*, 2004]. Similar variations in precipitation with topographic position are anticipated for

0094-8276/05/2005GL023759$05.00

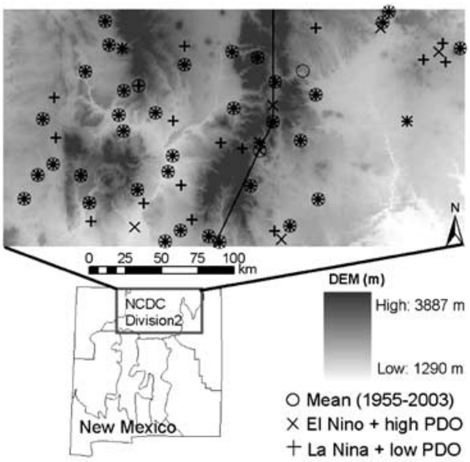

Figure 1. The study area in northern New Mexico with long-term mean gauge distribution, and two selected category-mean gauge distributions. Circles are gauges with long-term precipitation records (1955–2003); crosses are gauges with more than 2 years of El Nino + high PDO data; and pluses are gauges with more than 2 year of La Nina + low PDO data. A 1-km DEM is shown in the background. The solid line is an approximate boundary for two different climate sub-regions identified later in this study.

PDO. Sufficiently dense gauge networks are unavailable to assess the orographic patterns induced by ENSO and PDO, and their potential interactions. As a result, new methods for mapping the spatial and temporal variability of mountain precipitation using gauge data would be valuable.

[6] In this study, we examine the relation between seasonal precipitation and ENSO and PDO variability in a mountainous region of northern New Mexico using temporal analysis of rain gauge records and spatial patterns derived from a high-resolution precipitation-mapping tool. In our analysis, we treat the effects of PDO independently from ENSO, despite their likely physical relationship, and also evaluate the El Niño and La Niña phases separately. We examine the spatial and orographic patterns induced by atmospheric variability for seasonal precipitation.

2. Methodology

2.1. Study Area and Precipitation Data

[7] Our major objective is to determine atmospheric teleconnection patterns in mountainous terrain by using a spatial precipitation interpolation of interest in hydrologic applications. An NCDC climate division (Division 2) in northern New Mexico was chosen due to its terrain variability (Figure 1). The study area is composed of mountains and inter-mountain valleys, and serves as headwaters for several basins. Elevation ranges from 1290 to 3887 m according to a 1-km digital elevation model (DEM). Over 130 NCDC stations are available in the area. However, for the purpose of this study, only gauges from 1955–2003 (49 yrs, with equal high PDO and low PDO years) were used to study the seasonal patterns of precipitation variability. The selected data span is a compromise between the gauge record length and spatial density, and the need to cover at least one PDO phase shift. The gauge locations used to estimate the long-term mean precipitation and two selected ENSO + PDO categories (see below) are shown in Figure 1.

2.2. Categorization of ENSO and PDO Years

[8] In contrast to studies using a concurrent or lag correlation between precipitation and climate indices, we determine the anomaly of mean seasonal precipitation for years with a certain ENSO and PDO phase combination. For hydrologic reasons, an ENSO year was defined from October through the next September (a water year), including the peak and decaying stages of an ENSO extreme phase. With this definition, the implied connection between a summer season and its previous autumn may be misleading because of years when ENSO effects terminate abruptly in the spring. For simplicity, the year in which October occurs was used to label the ENSO year. With three ENSO phases (El Niño, La Niña, neutral) and two PDO phases (low PDO before 1976 and high PDO afterwards [*Mantua et al.*, 1997]), all years between 1955 and 1997 were classified into six groups (see Table 1). An ENSO extreme year (El Niño or La Niña) was identified when two or more of the following indices agree: JMA's SST anomalies (JMA-SSTA), NOAA's CPC SSTA (3 month running mean of ERSST.v2 SSTA), and *Gershunov and Barnett* [1998]. A year that does not meet at least two of the criteria was categorized as ENSO neutral phase. Because consensus does not exist regarding a PDO shift in late 1990s [*Hoerling and Kumar*, 2003], the years after 1997 were not included in the categories, but were considered when determining the long-term mean precipitation.

2.3. Data Analyses

[9] The anomaly, or systemic deviation, of mean seasonal precipitation of an ENSO + PDO category from the long-term average was considered evidence of a teleconnection effect. Precipitation deviations were calculated, for each gauge, by subtracting the long-term average from the category-mean precipitation for each category (Table 1). The long-term average monthly precipitation was calculated for 37 gauges with data from 1955 to 2003 (<5 yr of missing data). The category-mean monthly precipitation for each gauge was calculated for each ENSO + PDO category with available data (>2 yr). To minimize the influence of atmospheric variability, the monthly data was pooled into seasonal data, separated as fall (October), winter (November to March), spring (April to June) and summer (July to September) for hydrologic reasons. We included November and March into winter since precipitation could be in form of snow. The summer season captures the North American Monsoon. The seasonal values were calculated for each gauge by summing the monthly values; their difference gave the seasonal deviation for each gauge and category.

Table 1. Classification of Years Into Six ENSO + PDO Categories Based on the Various ENSO and PDO Phases Over the Period 1955–1997 (Each Year Covers From October of the labeled Year Through the Next September)

ENSO phases	High PDO	Low PDO
Warm phase (El Niño)	76 82 86 87 91 94 97	57 63 65 68 69 72
Cold phase (La Niña)	84 88	55 64 67 70 71 73 74 75
Neutral phase	77 78 79 80 81 83 85 89 90 92 93 95 96	56 58 59 60 61 62 66

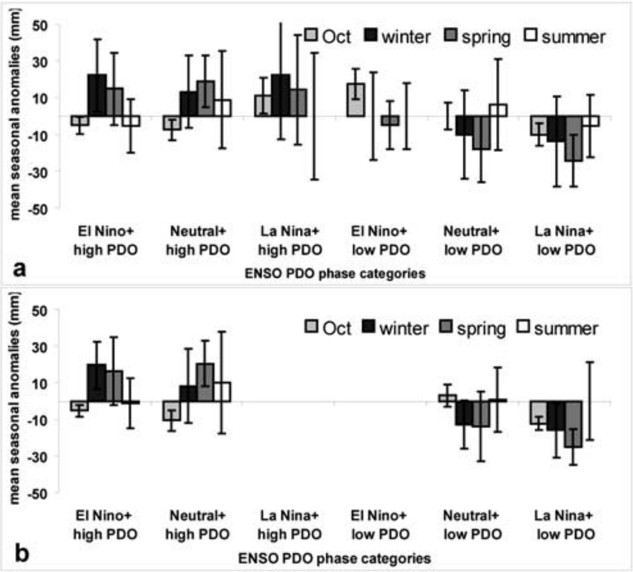

Figure 2. The seasonal precipitation anomaly of each ENSO + PDO category, (a) averaged over all available gauges, and (b) averaged over all pixels from ASOADeK model results. For each category and season, the error bar is one standard deviation of the spatially averaged precipitation anomaly of all available gauges over the period of observation. The error represents spatial variability (apparent in Figures 3 and 4) and even some temporal variability, as the available years of each category are not necessarily identical between gauges. Spatial variability is often neglected in climate studies based on climate division mean precipitation.

The gauge deviations for each category were spatially averaged. Spatially averaged seasonal anomalies were considered significant when exceeding the standard deviation of a 50-year moving average of seasonal precipitation; otherwise, the anomaly was set to zero. Calculated for 22 gauges (1931–2003), the moving average had a mean standard deviation (mm) of 1.2, 3.5, 3.1, 4.4 for fall, winter, spring and summer.

[10] To examine the spatial variability of the precipitation anomalies, we used a high-resolution precipitation-mapping tool, ASOADeK (Auto-Searched Orographic and Atmospheric effects De-trended Kriging) [*Guan et al.*, 2005]. ASOADeK employs a multivariate linear regression approach to auto-search regional and local climatic settings and local orographic effects. The observed gauge precipitation data are then de-trended by the auto-searched regression surface. The de-trended gauge data are further interpolated by ordinary kriging to generate a de-trended precipitation residual surface. The precipitation map is then constructed by adding the regression surface to the residual surface. Monthly precipitation maps were constructed using ASOADeK for the long-term mean, two categories of constructive ENSO and PDO, and two categories of the neutral ENSO phase, each at a 1 km resolution. Monthly category-mean precipitation maps were summed to create seasonal maps, and compared to the long-term mean seasonal precipitation, to find systematic spatial features of precipitation anomalies and orographic effects in the study area. To reduce the ASOADeK uncertainty, only pixels within the elevation of 1500 to 2700m (where most gauges are located) were used for the analysis.

3. Results

[11] The seasonal pattern of ASOADeK precipitation anomalies is consistent with that of gauge-average anomalies for the selected ENSO + PDO categories (Figure 2). Of the four seasons, winter and spring precipitation anomalies appear to be consistently connected to ENSO and PDO. For the high PDO phase categories, both winter and spring seasons have positive anomalies (~10–20%). For the low PDO phase categories, the ENSO neutral and La Niña categories have significant negative winter and spring precipitation anomalies (~10% winter, and ~20% spring). The low PDO + El Niño category does not have an observable winter anomaly, although a small negative spring anomaly is observed (~5%). From this analysis, based on one PDO cycle, it appears that PDO has a dominant effect on winter and spring precipitation, with a wetter winter and spring for high PDO, and a dry winter and spring for low PDO.

[12] The effects of ENSO extreme phases are determined by comparisons to the ENSO neutral phase having the same PDO phase. El Niño strongly dampens negative anomalies in winter and spring of the low PDO years, but does not enhance positive anomalies in the high PDO years. La Niña modestly enhances negative anomalies in winter and spring of the low PDO years, but does not have an effect in the high PDO years.

[13] Spatial patterns and topographic modulations of ENSO and PDO effects are clearly observed in Figures 3 and 4. Winter precipitation anomalies strongly depend on the elevation. For a wetter-than-normal winter, the anomalies are larger at higher elevations, and are positive. For a drier-than-normal winter, the anomalies are larger at lower elevations, and are negative. Elevation does not appear to significantly affect summer precipitation anomalies, nor do we observe topographic controls on spring or October precipitation anomalies (not shown) The results indicate

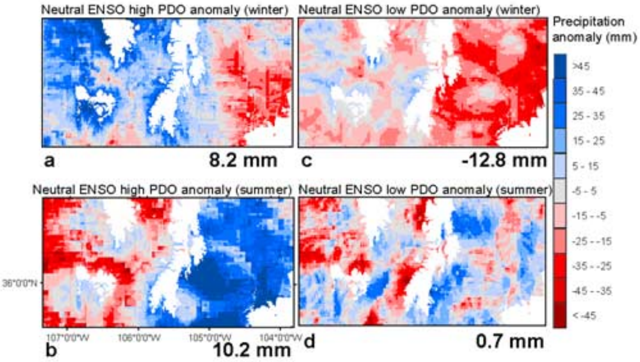

Figure 3. Winter and summer precipitation anomalies (deviations) for categories of (a) and (b) high PDO and (c) and (d) low PDO with neutral ENSO. The number for each panel is the mean pixel anomaly. The winter-summer pixel based correlation is −0.48 for both a,b and c,d pairs. The white pixels are outside the elevation range of 1500 to 2700 m.

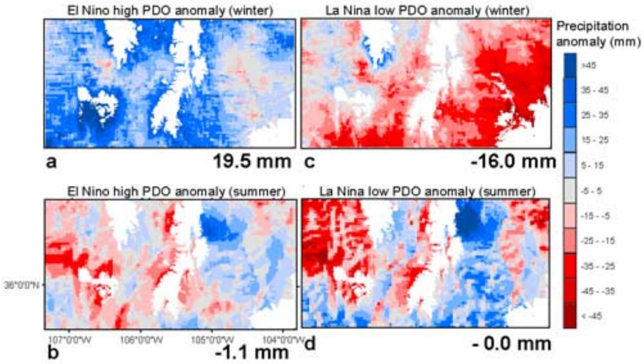

Figure 4. Winter and summer precipitation anomalies (deviations) for categories of (a) and (b) El Niño + high PDO, and (c) and (d) La Niña + low PDO. The number for each panel is the mean pixel anomaly. The winter-summer pixel based correlation is −0.26 for Figures 4a and 4b and −0.30 for Figures 4c and 4d pairs. The white pixels are outside the elevation range of 1500 to 2700 m.

that terrain elevation modulates ENSO and PDO effects in winter, but not other seasons. For some seasons and categories, the pattern of anomalies differ between the eastern and western portions of the study area (see Figure 1), especially for spring (not shown) and summer precipitation.

[14] Figure 2 suggests that, spatially averaged over the region, summer precipitation does not seem to be well correlated with ENSO or PDO. In addition, in Figure 2, summer precipitation does not appear to be related to the antecedent winter precipitation, as a wetter-than-normal winter does not lead to a drier-than-normal summer (given our use of a water year this result could be misleading due to years when ENSO effects terminate abruptly in the spring). However, if the eastern and western portions (Figure 1) are considered separately, summer precipitation anomalies appear to be negatively correlated to the preceding winter precipitation anomalies (Figures 3 and 4), especially for neutral ENSO (Figure 3). Differences in precipitation anomalies in these two areas suggest that they are climatically distinct and should not be treated within the same climate division. Similar problems have been generally noticed for NCDC climate divisions [*Guttman and Quayle*, 1996]. This is an important issue for water management in this area because the two areas serve as water sources for different river systems.

4. Conclusions

[15] This study uses instrument records and geostatistical modeling to examine temporal and spatial patterns of seasonal precipitation anomalies by relating them to ENSO and PDO. High-resolution mapping brings out hydrologically important patterns of the precipitation anomalies that would otherwise be blurred by spatial averaging. Both spatial averages and maps suggest that PDO is the dominant teleconnection for winter and spring precipitation in the study region, with high PDO leading to wetter-than-normal conditions, and low PDO leading to opposite effects. Extreme ENSO effects are significant during the low PDO years, with El Niño strongly dampening winter and spring precipitation anomalies. From the spatial analysis, the PDO and ENSO controls on winter precipitation are modified by topography, with larger anomalies at high elevations for wetter-than-normal winters, and larger anomalies at low elevations for drier-than-normal winters. Averaged over the study area (one NCDC climate division), the summer precipitation anomaly is not related to ENSO, PDO or the precipitation of the previous winter. If evaluated, instead, in western and eastern sub-areas, the summer precipitation anomalies appear to be negatively correlated to the preceding winter precipitation anomalies, especially for neutral ENSO.

[16] **Acknowledgment.** This work was supported by the SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) under the NSF-STC Program EAR-9876800, and partially by the NSF (EAR-0342526), and benefited from excellent anonymous reviews.

References

Adams, D. K., and A. C. Comrie (1997), The North American monsoon, *Bull. Am. Meteorol. Soc.*, *78*, 2197–2213.
Andrade, E. R., and W. D. Sellers (1988), El Niño and its effect on precipitation in Arizona and western New Mexico, *J. Climatol.*, *8*, 403–410.
Barlow, M., S. Nigam, and E. H. Berbery (2001), ENSO, Pacific decadal variability, and U.S. summertime precipitation, drought, and stream flow, *J. Clim.*, *14*, 2105–2128.
Castro, C. L., T. B. McKee, and R. A. Pielke Sr. (2001), The relationship of the North American monsoon to tropical and North Pacific sea surface temperatures as revealed by observational analyses, *J. Clim.*, *14*, 4449–4473.
Dettinger, M., K. Redmond, and D. Cayan (2004), Winter orographic precipitation ratios in the Sierra Nevada—Larger-scale atmospheric circulations and hydrologic consequences, *J. Hydrometeorol.*, *5*, 1102–1116.
Gershunov, A., and T. P. Barnett (1998), Interdecadal modulation of ENSO teleconnections, *Bull. Am. Meteorol. Soc.*, *79*, 2715–2725.
Goodrich, G. B. (2004), Influence of the Pacific decadal oscillation on Arizona winter precipitation during years of neutral ENSO, *Weather Forecasting*, *19*, 950–953.
Gray, S. T., J. L. Betancourt, C. L. Fastie, and S. T. Jackson (2003), Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains, *Geophys. Res. Lett.*, *30*(6), 1316, doi:10.1029/2002GL016154.
Guan, H., J. L. Wilson, and O. Makhnin (2005), Geostatistical mapping of mountain precipitation incorporating auto-searched effects of terrain and climatic characteristics, *J. Hydrometeorol.*, in press.
Guttman, N. B., and R. G. Quayle (1996), A historical perspective of U.S. climate divisions, *Bull. Am. Meteorol. Soc.*, *77*, 293–304.
Gutzler, D. S., D. M. Kann, and C. Thornbrugh (2002), Modulation of ENSO-based long-lead outlooks of southwestern U.S. winter precipitation by the Pacific decadal oscillation, *Weather Forecasting*, *17*, 1163–1172.
Higgins, R. W., and W. Shi (2000), Dominant factors responsible for interannual variability of the summer monsoon in the southwestern United States, *J. Clim.*, *13*, 759–776.
Hoerling, M., and A. Kumar (2003), The perfect ocean for drought, *Science*, *299*, 691–694.
Kunkel, K. E., and J. R. Angel (1999), Relationship of ENSO to snowfall and related cyclone activity in the contiguous United States, *J. Geophys. Res.*, *104*, 19,425–19,434.
Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.
Ropelewski, C. F., and M. S. Halpert (1986), North American precipitation and temperature patterns associated with the El Niño-Southern Oscillation (ENSO), *Mon. Weather Rev.*, *114*, 2352–2362.
Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and J. K. Hughes (2002), The climate of the US Southwest, *Clim. Res.*, *21*, 219–238.
Simpson, H. J., and D. C. Colodner (1999), Arizona precipitation response to the Southern Oscillation: A potential water management tool, *Water Resour. Res.*, *35*, 3761–3769.

H. Guan, E. R. Vivoni, and J. L. Wilson, Earth and Environmental Science, New Mexico Tech, 801 Leroy Place, MSEC 242, Socorro, NM 87801, USA. (jwilson@nmt.edu)