

A winter precipitation ‘dipole’ in the western United States associated with multidecadal ENSO variability

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Received 29 September 2003; revised 24 March 2004; accepted 7 April 2004; published 6 May 2004.

[1] The variability of winter precipitation across the western United States has important implications for a wide range of physical and socioeconomic systems. While El Niño-Southern Oscillation (ENSO) teleconnections explain a high degree of interannual variance in western U.S. winter precipitation, their influence on decadal time scales is less well understood. In this study, we examine the relationship between ENSO conditions and winter precipitation in the western U.S. within the context of decadal-scale variability, as represented by phasing of the Pacific Decadal Oscillation (PDO). We identify spatial inconsistencies in the ENSO-precipitation relationship, commensurate with PDO phase shifts, which take the form of a ‘dipole’ signature across the western U.S. This finding has implications for the knowledge of uncertainty of ENSO teleconnections, and may prove meaningful for users of climate information throughout the region.

INDEX TERMS: 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 4215 Oceanography: General: Climate and interannual variability (3309); 4522 Oceanography: Physical: El Niño. **Citation:** Brown, D. P., and A. C. Comrie (2004), A winter precipitation ‘dipole’ in the western United States associated with multidecadal ENSO variability, *Geophys. Res. Lett.*, 31, L09203, doi:10.1029/2003GL018726.

1. Introduction

[2] Winter precipitation variability in the western United States impacts a wide range of physical and socioeconomic systems, with associated costs and damages that can total \$3 billion annually [Lott et al., 1997; Dettinger et al., 1998]. Users of climate information throughout the region therefore desire advance forecasts of winter precipitation in order to address the impacts of its variability and augment their decisions regarding resource management. The bulk of the skill and confidence in these forecasts is provided by the El Niño-Southern Oscillation (ENSO), a 2–7 year cycle of equatorial sea surface temperature (SST) anomalies in the eastern Pacific Ocean that comprises the leading mode of interannual precipitation variability in the western U.S. [Horel and Wallace, 1981; Trenberth, 1997; Gershunov and Barnett, 1998]. During the winter season, cool ENSO conditions (La Niña) are typically linked to above-normal precipitation in the Pacific Northwest and below-normal precipitation in the Southwest [Kiladis and Diaz, 1989], while approximately opposite conditions hold true when ENSO is in its warm state (El Niño). Current NOAA

measurements and analyses permit the forecasting of winter precipitation anomalies in the western U.S., based on interannual ENSO conditions, as many as 6–9 months ahead of time [Barnston et al., 1994; Latif et al., 1994; Hamlet and Lettenmaier, 1999].

[3] Recently, a decadal pattern of SST variability in the Pacific has also been identified, one that is characterized by a spatial structure similar to ENSO [Zhang et al., 1997] but with greater amplitude at high latitudes and a reduced tropical expression [Gedalof et al., 2002]. The dynamics of this Pacific Decadal Oscillation, or PDO [Mantua et al., 1997], are not yet fully understood, but it may represent the integration of interannual ENSO variability into the decadal SST signature [Livezey and Smith, 1999; Newman et al., 2003]. The impacts of persistent, multi-year winter precipitation anomalies in the western U.S. associated with this decadal pattern of Pacific variability are crucial for water supply issues, biota health, and high-frequency flood and drought occurrence throughout the region [Cayan et al., 1998].

[4] Because the PDO exhibits pronounced “phase shifts” at 20-to-30 year intervals [Mantua et al., 1997], an index of the PDO may be diagnostically useful for characterizing the degree of interannual ENSO variability within these 20-to-30 year time periods, and in identifying decadal-scale ENSO impacts on the western U.S. [Cole and Cook, 1998]. The pronounced difference in ENSO-based predictability of winter precipitation in the Southwest U.S. before and after the 1977 PDO phase shift [Gutzler et al., 2002], and the spatial variability of precipitation anomalies in the western U.S. on decadal time scales [Cayan et al., 1998; Dettinger et al., 1998], for example, suggest that it may be necessary to analyze interannual ENSO teleconnections while also considering decadal-scale variability [Gershunov and Barnett, 1998; McCabe and Dettinger, 1999; Higgins et al., 2000].

2. Objective

[5] In this study, we examine the relationship between ENSO conditions and winter precipitation in the western U.S. within the context of decadal-scale variability. We identify inconsistencies in the ENSO-precipitation relationship that vary spatially commensurate with PDO phase shifts; in particular, we highlight a teleconnection ‘dipole’, distinct from the findings of earlier studies, wherein El Niño (La Niña) events during the fall season precede atypical winter precipitation anomalies in the Southwest (Northwest) during cool (warm) phases of the PDO. The findings presented here have implications for the knowledge of uncertainty of decadal-scale ENSO impacts in the western

U.S., and may prove meaningful for stakeholders throughout the region who utilize climate information in their decision-making processes.

3. Data and Methods

[6] Monthly precipitation data for 84 climate divisions in the western U.S. were obtained from the National Climate Data Center (<http://www.ncdc.noaa.gov>). Time series of total winter season precipitation were calculated for each climate division for the period 1925–1995, with the winter season defined as December–February. Since the choice of winter season length did not significantly affect the results of previous studies [e.g., Gutzler *et al.*, 2002], the December–February period was selected because ENSO impacts in the western U.S. are strongest during these months [Diaz *et al.*, 2001].

[7] The Southern Oscillation Index (SOI), a measure of the difference in normalized pressure anomalies between Tahiti and Darwin, Australia, was utilized to capture ENSO variability. In some cases, SST time series may be more desirable than the atmospherically based SOI for representing ENSO. In this instance, however, the continuous observational record of the SOI since 1925, the successful use of the index in previous western U.S. climate analyses [e.g., Redmond and Koch, 1991; Piechota and Dracup, 1996; Piechota *et al.*, 1997; Garen, 1998; Harshburger *et al.*, 2002], and recent studies suggesting that the SOI compares favorably with major SST indices [e.g., Hanley *et al.*, 2003], made it an appropriate measure of ENSO variability. Monthly SOI data were obtained from the Climate Prediction Center (<http://www.cpc.noaa.gov>), and a three-month average for the fall season (September–November) was calculated for the period 1925–1995. The state of ENSO during the fall season is of particular utility in forecasting winter precipitation in the western U.S., when the lagged relationship between SST anomalies and precipitation is strongest [Harshburger *et al.*, 2002]. This relationship has been useful in identifying decreases (increases) in winter precipitation in the Pacific Northwest following fall season El Niño (La Niña) events [Redmond and Koch, 1991], and has contributed skill to streamflow forecasts in the same region [Hamlet and Lettenmaier, 1999]. Individual fall seasons with normalized SOI anomalies of -0.4 ($+0.4$) were classified as El Niño (La Niña).

[8] Previous analyses have shown that interannual values of the PDO index do not improve ENSO-based predictability of winter precipitation in the western U.S. [e.g., Gutzler *et al.*, 2002; R. E. Livezey, personal communication, 2003], likely because of the index's integration of overall conditions in the North Pacific on monthly-to-annual time scales [Hamlet and Lettenmaier, 1999]. Therefore, rather than employ the PDO index itself, the variability of interannual ENSO-precipitation relationships were examined within discrete PDO “phases”, characterized by persistent, multi-decadal warm (positive) or cool (negative) SST anomalies in the North Pacific. Three major 20th century PDO “phase shifts” occurred during the years 1925, 1947, and 1977 [Minobe, 1997; Hamlet and Lettenmaier, 1999; Gedalof *et al.*, 2002]. Poor quality of western U.S. climate division precipitation data limits the investigation of pre-1925 conditions, and although evidence suggests that the PDO

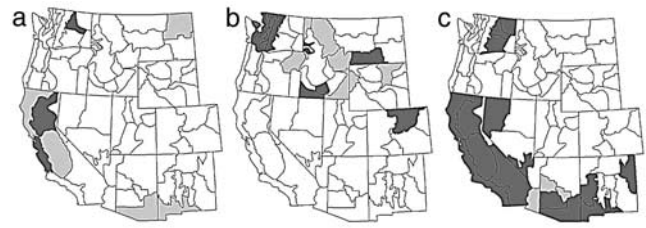


Figure 1. Pearson correlation coefficients calculated for fall (SON) SOI and winter (DJF) precipitation for three PDO phases: (a) warm, 1925–1946; (b) cool, 1947–1976; (c) warm, 1977–1995. Statistically significant correlations are shown at the $\alpha = 0.10$ (light shading) and $\alpha = 0.05$ (dark shading) levels.

shifted into a cool phase during the mid-to-late 1990's [Mantua and Hare, 2002], it may take several years to identify the exact timing of the shift [Chavez *et al.*, 2003; Newman *et al.*, 2003]. As a result, the analyses were bound at 1925 and 1995, and ENSO-precipitation relationships considered during three distinct PDO phases: 1925–1946 (warm), 1947–1976 (cool), and 1977–1995 (warm).

[9] Pearson correlation coefficients were calculated for each PDO phase using the fall SOI and winter climate division precipitation time series. This type of covariate analysis, using seasonal lags, has been previously shown to have predictive value in western U.S. climate analyses [e.g., Redmond and Koch, 1991]. Statistically significant correlations ($\alpha = 0.10$ and $\alpha = 0.05$ levels) were mapped to show spatial variability in the ENSO-precipitation relationship between differing PDO phases. Winter precipitation anomalies (percent-of-normal precipitation) were also calculated, first for all winters in the 1925–1995 study period, then for each of the three PDO phases. These precipitation anomalies were calculated for winters following fall season El Niño and La Niña conditions, respectively. The 1925–1995 precipitation anomalies were used to highlight the “canonical” winter precipitation patterns in the western U.S. following warm and cool ENSO anomalies during the fall season, while the precipitation anomalies for the 1925–1946, 1947–1976, and 1977–1995 periods were used to augment the correlation analyses and further illustrate spatial variability in the ENSO-precipitation relationship over time.

4. Results

[10] The spatial inconsistency of fall ENSO-winter precipitation relationships in the western U.S. is clearly revealed by the Pearson correlation analysis (Figure 1). During the most recent (1977–1995) warm period, highly significant correlations between fall (SON) ENSO and winter (DJF) precipitation dominate the Southwest, including southern Arizona, parts of New Mexico and Nevada, and all of California (Figure 1c). At the same time, no significant relationships are seen in the Pacific Northwest or northern Rockies, with a single exception of an isolated area along the interior Columbia River Basin in eastern Washington. The cool PDO phase of 1947–1976 reveals spatial relationships in stark contrast to those of the 1977–1995 warm period, with statistically significant correlations in



Figure 2. Winter (DJF) precipitation anomalies for the period 1925–1995 following (a) El Niño ($n = 20$) and (b) La Niña ($n = 19$) events during the fall (SON) season as defined by a ± 0.4 normalized SOI anomaly threshold. Dry (wet) anomalies of less than 85% (greater than 115%) of normal are highlighted in light (dark) shading.

parts of Washington, Idaho, Montana, Oregon, Wyoming, and Colorado, but no significant correlations anywhere in the Southwest (Figure 1b). The 1925–1946 warm period correlations mirror those of the 1977–1995 period, albeit more weakly (Figure 1a), a fact that may be due to fewer individual station inputs into the climate division record during this period.

[11] Figure 2 shows percent-of-normal winter (DJF) precipitation in the western U.S. following fall El Niño (Figure 2a) and fall La Niña (Figure 2b) episodes for the entire 1925–1995 period. As expected, these anomalies reveal the canonical patterns of winter precipitation associated with fall ENSO conditions. In the Southwest, wet winters tend to follow fall El Niño events, while dry winters follow La Niña. In the Northwest, the anomalies are somewhat less robust, but drier-than-average winter conditions tend to prevail following El Niño, with wet winters being preceded by La Niña conditions.

[12] When winter precipitation anomalies are examined for each of the three PDO phases separately, however, the source of the marked spatial variability in the Pearson correlation analysis becomes clearer. For winters following fall El Niño episodes (Figure 3), it is evident that the Southwest does not always experience predominantly wet conditions. During the cool PDO phase from 1947–1976 (Figure 3b), drier-than-normal winters prevailed across the entirety of the interior Southwest, with dry anomalies extending northward into Utah, Colorado, and Wyoming as well as westward into Nevada. This cool PDO phase coincided with a period of severe drought in the Southwest that peaked in the mid-1950's [Sheppard *et al.*, 2002]. In



Figure 3. Winter (DJF) precipitation anomalies following El Niño conditions during the fall (SON) season, stratified by PDO phases: (a) warm, 1925–1946, $n = 5$; (b) cool, 1947–1976, $n = 8$; (c) warm, 1977–1995, $n = 7$. Anomalies are shaded as in Figure 2.

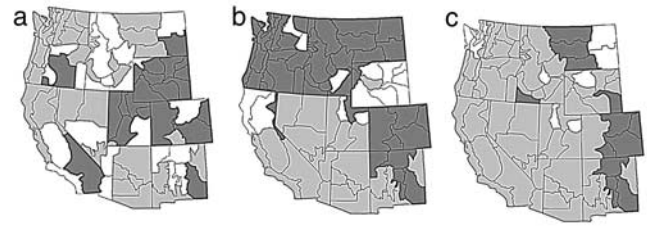


Figure 4. Winter (DJF) precipitation anomalies following La Niña conditions during the fall (SON) season, stratified by PDO phases: (a) warm, 1925–1946, $n = 6$; (b) cool, 1947–1976, $n = 12$; (c) warm, 1977–1995, $n = 3$. Anomalies are shaded as in Figure 2.

contrast, winter precipitation anomalies following fall El Niño events were much more canonical in the Southwest during the 1925–1946 and 1977–1995 warm PDO periods (Figures 3a and 3c), with wetter-than-average conditions evident in both periods across large portions of Arizona, New Mexico, and California.

[13] Shifts between warm and cool PDO phases did not appear to have a significant impact on the relationship between fall season El Niño events and winter precipitation anomalies in the Northwest. However, this was not the case when fall La Niña episodes were examined (Figure 4). Only during the cool PDO phase of 1947–1976 (Figure 4b) did the Northwest experience “canonical” wet winters following fall La Niña conditions. During the two PDO warm phases (Figures 4a and 4c), drier-than-average or near-normal winter conditions persisted across both the coastal and interior regions of the Northwest following fall season La Niña events, including significant portions of Washington, Oregon, Idaho, and Montana. In the Southwest, dry winters tended to consistently follow fall La Niña episodes regardless of PDO phase.

5. Conclusions

[14] The findings presented here highlight spatial inconsistencies in the relationship between ENSO and winter precipitation in the western U.S. Correlations between fall ENSO and winter precipitation vary spatially commensurate with PDO phase shifts, wherein a strong ENSO signal is evident in the Southwest (Northwest) only during warm (cool) phases of the PDO. More specifically, the results suggest that when PDO is in its cool (warm) phase, fall season El Niño (La Niña) events often precede non-canonical winter precipitation anomalies in the Southwest (Northwest). The identification of this ‘dipole’ signature, by which the predictable ENSO signal essentially “switches off” in either the Northwest or Southwest, highlights the uncertainty surrounding ENSO impacts on decadal time scales, and complements the findings of previous studies such as Gershunov and Barnett [1998]. By showing that ENSO-based predictability of winter precipitation in the western U.S. varies both spatially and temporally concomitant with PDO phasing, we demonstrate the need for cautious and informed use of ENSO-based seasonal forecasts as well as the necessity to further articulate the physical underpinnings of the PDO pattern. Our analyses contribute to a broad understanding of ENSO-PDO impacts, and provide a mech-

anism for improved operational understanding in the sense of recognizing new limitations in ENSO-based forecasting.

[15] Recent patterns of Pacific-wide SST anomalies [Hoerling and Kumar, 2003] are consistent with a growing body of evidence suggesting that La Niña may be the dominant ENSO phase for the next ~15–20 years. If true, the next two decades could be marked by a decrease in the reliability of fall season El Niño conditions as a predictor of above-average winter precipitation in the Southwest, and vice versa for La Niña in the Northwest. The repeated occurrence of anomalously dry winters in the Southwest during the coming 10-to-20 years could exacerbate drought conditions throughout the region, where winter season precipitation constitutes a significant portion of the annual water budget. Further diagnostic analyses are therefore essential in order to better understand the decadal-scale impacts of ENSO anomalies on winter precipitation throughout the western United States.

[16] **Acknowledgments.** We thank Gregg Garfin, Michael Crimmins and two anonymous reviewers for comments on an earlier version of this manuscript. The NOAA Office of Global Programs, through the Climate Assessment Project for the Southwest (CLIMAS) at the University of Arizona, provided support for this research.

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