Oceanic-Atmospheric Variability and Western U.S. Snowfall

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Citation of published version:
Hunter, T., Tootle, G., Piechota, T. (2006): Oceanic-Atmospheric Variability and Western U.S. Snowfall. *Geophysical Research Letters,* 33(13).
DOI: https://doi.org/10.1029/2006GL026600

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L13706, doi:10.1029/2006GL026600, 2006

Oceanic-atmospheric variability and western U.S. snowfall

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Received 14 April 2006; revised 31 May 2006; accepted 7 June 2006; published 8 July 2006.

[1] A study of the influences of interdecadal and interannual oceanic-atmospheric influences on April 1 Snow-Water Equivalent (SWE) in the western U.S. is presented. SWE data was identified at 323 Natural Resources Conservation Service (NRCS) SNOTEL (SNOwpack TELemetrysites) stations for the period of 1961 to 2004 and for 121 SNOTEL stations for the period 1941 to 2004. The phases (cold/negative or warm/positive) of Pacific Ocean [El Niño -Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)] and Atlantic Ocean [Atlantic Multidecadal Oscillation (AMO) and North Atlantic Oscillation (NAO)] oceanic-atmospheric influences were identified for the year prior to the SWE data set. Statistical significance testing of SWE data set, based on the interdecadal and interannual oceanic-atmospheric phase (warm/positive or cold/negative) was performed by applying the nonparametric rank-sum test. The results show that in addition to the well established ENSO signal in the northwest, the PDO and AMO influence SWE variability. Additionally, the coupled effects of the oceanic-atmospheric influences were evaluated on the basis of the long-term phase (cold/negative or warm/positive) of the interdecadal (PDO, AMO, NAO) influences and the interannual ENSO. Finally, the coupled effects of the oceanic-atmospheric influences were evaluated on the basis of the long-term phase (cold/negative or warm/positive) of the interdecadal (AMO, PDO, NAO) phenomena. Regions in the west were identified that responded to the interdecadal/decadal climatic coupling. By utilizing the April 1 SWE and the long lead-time approach for the oceanic-atmospheric variables, useful information can be provided to snow forecasters and water managers.

Citation: Hunter, T., G. Tootle, and T. Piechota (2006), Oceanic-atmospheric variability and western U.S. snowfall, *Geophys. Res. Lett.*, *33*, L13706, doi:10.1029/2006GL026600.

1. Introduction

[2] Oceanic-atmospheric variability have been shown to influence streamflow [*Tootle et al.*, 2005; *Rogers and Coleman*, 2003; *Enfield et al.*, 2001; *Kahya and Dracup*, 1993], precipitation [*Enfield et al.*, 2001; *Gershunov*, 1998] and snowfall [*McCabe and Dettinger*, 2002] in the United States. Based on the results of the streamflow and precipitation studies, regions of the western U.S. have demonstrated variability based on the phases of the ENSO, PDO, AMO and NAO. In the western U.S., snowpack is an important source of runoff and water supply, accounting for 50 to 70 percent of the annual precipitation in the mountainous regions. In the western U.S., the April 1 SWE provides estimates and forecasts of the eventual total annual runoff [*McCabe and Dettinger*, 2002]. Water managers and forecasters, when provided predictive information about the April 1 SWE, may improve estimates of spring-summer runoff which is critical in the management of reservoirs and irrigation practices.

[3] This research improves on previous studies by utilizing SNOTEL data (April 1 SWE) for the western U.S. and by extending the period of record to include recent data. Next, a lead time approach is adopted such that the previous year (or season) interdecadal (interannual) atmospheric-oceanic variability is used to evaluate SWE variability. Additionally, non-parametric statistical testing is utilized to determine SWE response to atmospheric-oceanic variability, thus eliminating assumptions of normality or linearity. Finally, both interdecadal-interannual and interdecadal-interdecadal coupling are evaluated for both Pacific and Atlantic oceanic influences.

2. Data and Methodology

[4] Historic April 1 SWE data was obtained from the NRCS SNOTEL website (http://www.wcc.nrcs.usda.gov/snotel/) for stations in the western United States. The NRCS SNOTEL website combines SNOTEL data (obtained with remote sensing equipment) with snow course data (obtained with manual snow measurements) to develop the historic records. This resulted in 323 SNOTEL stations being identified with a period of record 1961 to 2004 (43 years), as well as 121 stations with a period of record 1941 to 2004 (63 years) (Figure 1). The 121 SNOTEL stations were selected for use in the current research due to the longer period of record. Of note, the same methodology was applied to the 323 station data set (results not provided) which resulted in similar findings when compared to the reported results of the 121 stations.

[5] *McCabe et al.* [2004] defined four periods for the PDO and AMO: PDO warm and AMO warm (1926–1943), PDO cold and AMO warm (1944–1963), PDO cold and AMO cold (1964–1976), and PDO warm and AMO cold (1977–1994). Recent studies suggest that the PDO returned to a cold phase around 2000 [*Mantua et al.*, 1997; *Hare and Mantua*, 2000] and the AMO returned to a warm phase in 1995 [*Enfield et al.*, 2001]. The periods for the PDO and AMO used in the *McCabe et al.* [2004] study were adopted for this study with the assumptions the PDO returns to cold in 2000 and the AMO returns to warm in 1995.

[6] *Hurrell and Van Loon* [1995] applied a low pass filter to the yearly NAO Index values to remove fluctuations of less than four years. This resulted in a negative phase during the early 1950s to early 1970s, a positive/negative fluctu-

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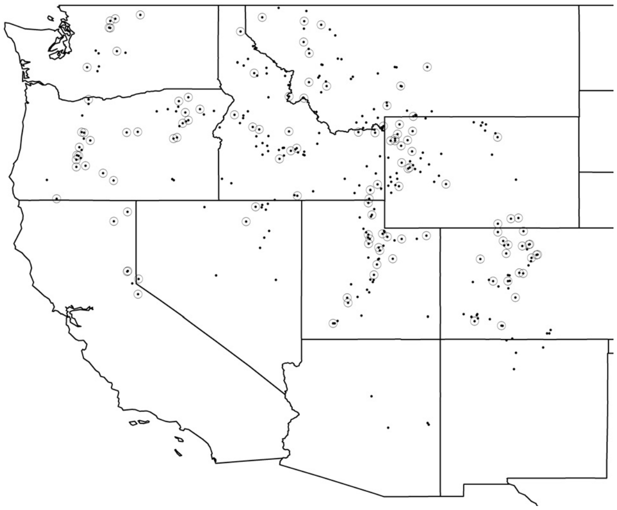


Figure 1. Location Map of SNOTEL Stations used in the study; points are stations (323) with a period of record 1961–2004 and circles are stations (121) with a period of record 1941–2004.

ation during the mid/late 1970s to early 1980s, and a positive (high) phase from the early 1980s to mid-1990s. When applying the low-pass filter to NAO Index values obtained from the NCAR website (http://www.cgd.ucar.edu/cas/jhurrell/indices.html), the NAO has maintained a positive phase into the early 2000's, a negative phase from 1944 to 1952, and a positive phase from the early 1930's to 1944. The NAO Index phases, as defined by *Hurrell and Van Loon* [1995] were used in this study with the NAO remaining in a positive phase from 1995 until the end of the period of record in 2004, a negative phase from 1944 to 1952, and a positive phase from the 1941 to 1944.

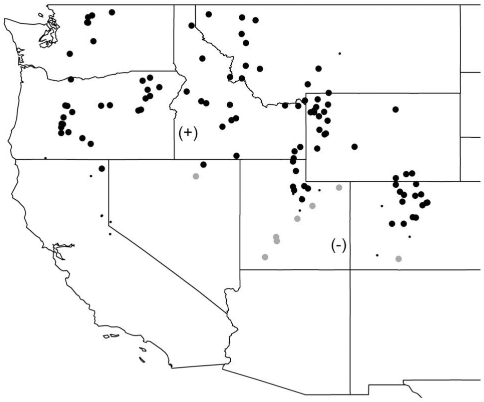
[7] *Gershunov and Barnett* [1998] defined a seasonal ENSO as when the Nino 3.4 index was above/below 0.8 times the standard deviation. They concluded that this value was high enough to exclude questionable ENSO events and would allow for an adequate number of ENSO events when combining the PDO [*Gershunov and Barnett*, 1998]. This method was applied to the Niño 3.4 index and Troup Southern Oscillation Index for the summer (May to September) season and the results (summer season ENSO years identified) were used to compliment the NOAA-CDC core summer season ENSO year data set (i.e., recognize and incorporate additional ENSO years).

[8] The previous year (or season) phase was used with the current year April 1 SWE to provide a lead time approach. Initially, the individual phase (warm/positive or cold/negative) of the interannual (ENSO) or interdecadal (PDO, AMO or NAO) variability on western April 1 SWE was evaluated. This was done by evaluating all the April 1 SWE values for each station based on the defined ENSO, PDO, AMO or NAO phase. Next, an evaluation of the impacts of the coupling of the interdecadal (PDO, AMO or NAO) variability with the interannual ENSO was performed. Finally, an evaluation of the impacts of the coupling of the interdecadal (PDO, AMO and NAO) variability was performed. Similar to *Tootle et al.* [2005], the non parametric rank sum test was utilized to determine significant (>90%) differences in April 1 SWE.

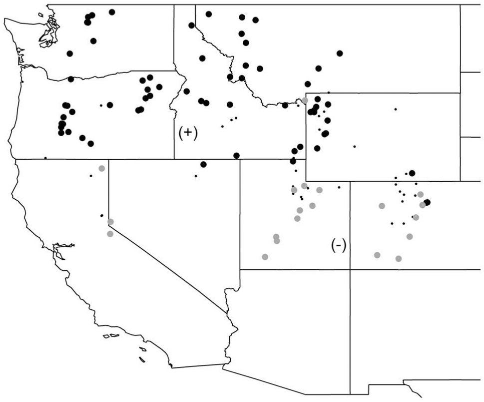
3. Results

3.1. Interannual (ENSO) and Interdecadal (PDO, AMO, and NAO) Testing

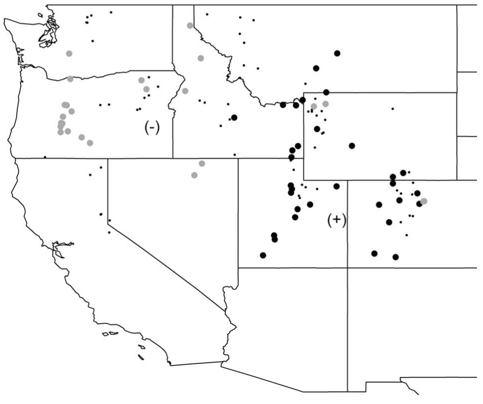
[9] The results show a strong ENSO signal was reaffirmed (Figure 2a). For the figures presented in the current research, a black (gray) circle represents a statistically



(a) ENSO cold (La Niña) - ENSO warm (El Niño)

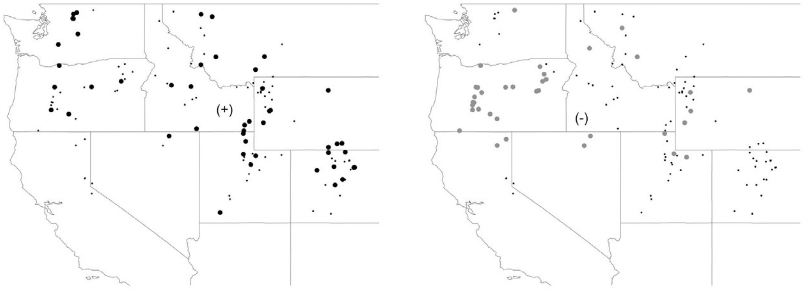


(b) PDO cold—PDO warm

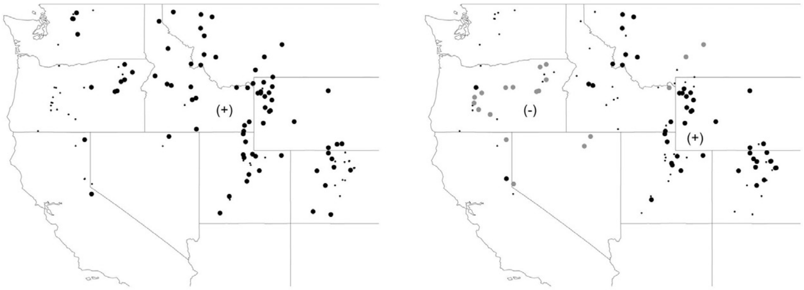


(c) AMO cold—AMO warm

Figure 2. Significant (90%) difference in April 1 SWE medians for (a) ENSO cold (La Niña) – ENSO warm (El Niño), (b) PDO cold – PDO warm, and (c) AMO cold – AMO warm. Positive (negative) significance is represented by black (gray) circles.



(a) PDO cold/La Niña - PDO warm (La Niña) **(c) AMO cold/El Niño - AMO warm (El Niño)**



(b) AMO cold/La Niña - AMO warm (La Niña) **(d) NAO positive/La Niña - NAO negative (La Niña)**

Figure 3. Significant (90%) difference in April 1 SWE medians for (a) PDO cold/La Niña – PDO warm/La Niña, (b) AMO cold/El Niño – AMO warm/El Niño, (c) AMO cold/La Niña – AMO warm/La Niña, and (d) NAO positive/La Niña – NAO negative/La Niña. Positive (negative) significance is represented by black (gray) circles.

significant (greater than 90%) positive (negative) difference in medians, such that the left side of the equation results in increased (decreased) SWE. A spatially smaller black "dot" represents a station that is not statistically significantly. For example, in Figure 2a, the black circles located in the Pacific Northwest were associated with increased SWE due to ENSO cold (La Niña), while the grey circles in southwestern Utah were associated with decreased SWE due to ENSO cold (La Niña). For both results, ENSO cold (La Niña) was tested against ENSO warm (El Niño). While a strong ENSO signal was not detected in southwest U.S. (and the Sierra Nevada Range), this was attributed to a lack of SNOTEL stations in this region (Figure 1). The ENSO north-south dipole, which has been established in streamflow and precipitation, was not as clearly defined in SWE. This could also be attributed to the lower frequency (but stronger magnitude) of ENSO events for the period of record (i.e., approximately the last fifty years).

[10] The PDO signal was reaffirmed in the Pacific Northwest and northern Rocky Mountains (Figure 2b). The Pacific Northwest and northern Rocky Mountains were associated with increased SWE due to the cold phase of the PDO when tested against the PDO warm phase. This was consistent with *McCabe and Dettinger* [2002] who identified high negative correlations between the seasonal PDO index and SWE in this region. Utah and Colorado were associated with decreased SWE due to the cold phase of the PDO when tested against the PDO warm phase. In the southwest, the PDO signal, while identified in streamflow [*Tootle et al.*, 2005], was not identified in SWE. As with the ENSO analysis noted above, there were insufficient SNOTEL stations in the southwest to make conclusions about the PDO influence on SWE data.

[11] The AMO signal was identified in western Oregon and the Rocky Mountains (Figure 2c). The AMO cold (when tested against the AMO warm phase) was associated with decreased SWE in this region. While *McCabe and Dettinger* [2002] did not evaluate Atlantic Ocean influences on SWE, the results were consistent with the findings of *Enfield et al.* [2001] whom identified the AMO index to be positively correlated with rainfall in the Pacific Northwest. The AMO cold (when tested against the AMO warm phase) was associated with increased SWE in Utah and Colorado. This result was again consistent with *Enfield et al.* [2001] whom identified the AMO index to be negatively correlated with rainfall in this region. Of note, an AMO signal was not identified in Utah and Colorado for streamflow [*Tootle et al.*, 2005] which may be attributed to summer monsoon activity.

[12] While the influence of the NAO was identified in approximately 40 (of 121) stations, there were no distinct spatial regions identified and therefore the results were not reported. This was consistent with previous studies that did not identify the NAO signal in the western U.S. streamflow and precipitation [*Tootle et al.*, 2005; *Visbeck et al.*, 2001].

3.2. Coupling of Interdecadal (PDO, AMO or NAO) and ENSO Testing

[13] The coupling of PDO and ENSO was evaluated by examining SWE relationships for PDO cold/El Niño – PDO warm/El Niño and PDO cold/La Niña – PDO warm/La Niña. The impact of the PDO phase on El Niño was not reported due to a small number of stations being identified. However, the PDO cold phase (given a La Niña) was associated with increased SWE in the Rocky Mountains when compared to the PDO warm phase (Figure 3a). As displayed in Figure 2a, La Niña was associated with

increased SWE in the Pacific Northwest and northern Rocky Mountains. Therefore, a PDO cold phase will likely enhance (strengthen) the influence of La Niña in this region, resulting in increased SWE. The results were consistent with *Gershunov and Barnett* [1998] who identified strong phases of El Niño/La Niña during similar phases (warm/cold) of the PDO. However, the results differed from *Tootle et al.* [2005] who did not identify a PDO influence of ENSO in continental U.S. streamflow.

[14] The coupling of AMO and ENSO was evaluated by examining SWE relationships for AMO cold/El Niño – AMO warm/El Niño and AMO cold/La Niña – AMO warm/La Niña. The AMO cold phase (given an El Niño) was associated with decreased SWE in the Oregon when compared to the AMO warm phase (Figure 3b). As displayed in Figure 2a, El Niño was associated with decreased SWE in Oregon and, therefore, the AMO cold phase will likely enhance (strengthen) the influence of El Niño in this region, resulting in decreased SWE. The AMO cold phase (given a La Niña) was associated with increased SWE in the northern and central Rocky Mountains when compared to the AMO warm phase (Figure 3c). As displayed in Figure 2a, La Niña was associated with increased SWE in the Rocky Mountains and, therefore, the AMO cold phase will likely enhance (strengthen) the influence of La Niña in this region, resulting in increased SWE. The coupling of AMO and ENSO was not previously identified for streamflow regions in the western United States [*Tootle et al.*, 2005].

[15] The coupling of NAO and ENSO was evaluated by examining SWE relationships for NAO positive/El Niño – NAO negative/El Niño and NAO positive/La Niña – NAO negative/La Niña. The impact of the NAO phase on El Niño was not reported due to a small number of stations being identified. For NAO positive/La Niña – NAO negative/La Niña, two regions (Oregon and northern Rocky Mountains) were identified with opposite behavior (Figure 3d). The negative (Oregon) result indicates that a La Niña during an NAO positive phase results in significantly less SWE than a La Niña during an NAO negative phase. The positive (Rocky Mountains) result indicates that a La Niña during an NAO positive phase results in significantly more SWE than a La Niña during an NAO negative phase. Physically, the NAO impacts the jet stream such that it shifts north during the positive phase and shifts south during the negative phase [*NOAA*, 2004] which may be influencing La Niña in this (RM) region.

3.3. Coupling of Interdecadals (PDO, AMO and NAO) Testing

[16] The coupling of the interdecadals (PDO, AMO and NAO) was evaluated by examining PDO cold/AMO cold, PDO warm/AMO Cold, PDO cold/AMO warm, PDO warm/AMO warm, AMO cold/NAO positive, AMO warm/NAO negative, AMO cold/NAO negative, AMO warm/NAO positive, PDO cold/NAO positive, PDO warm/NAO positive, PDO cold/NAO negative and PDO warm/NAO positive and the resulting SWE variability. For each of these 12 combinations, non-parametric (rank-sum) testing was performed, comparing the associated years for the specific combination to the all-years data set. This results in the identification of interdecadal couplings that are statistically different from the long-term SWE. Of the 12 combinations, three combinations (PDO warm/NAO negative, PDO warm/AMO cold and PDO cold/AMO cold) were associated with statistically significant changes (positive or negative) in SWE (Figure 4). The authors acknowledge that the PDO and AMO are time series that have high autocorrelation, resulting in lower degrees of freedom (and less confidence) in the statistical significance of the results presented in Figure 4. A PDO warm/NAO negative was associated with decreased SWE in the Cascade Range of Washington and Oregon and the northwestern Montana/Idaho panhandle. The PDO warm/AMO cold was associated with decreased SWE in the Cascade Range of Oregon and the northwestern Montana/Idaho panhandle. The PDO cold/AMO cold was associated with increased SWE in eastern Idaho and southwestern Montana. Interestingly, *Hidalgo* [2004] determined the largest drought in the past 250 years (based on tree-ring reconstructions) in the Yellowstone basin occurred during a PDO warm/AMO warm cycle.

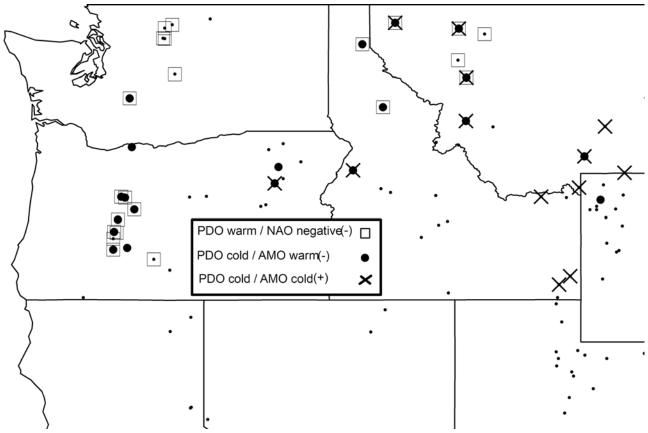


Figure 4. Significant (90%) difference in April 1 SWE medians for PDO warm/NAO negative – All-years (square), PDO warm/AMO cold – All-years (circle), and PDO cold/AMO cold – All-years (X).

4. Conclusions

[17] The current research reaffirmed previous results and provided several new contributions by evaluating Atlantic Ocean variability and by evaluating both interdecadal-interannual and interdecadal-interdecadal coupling. While the current research evaluated ENSO, the PDO, the AMO and the NAO, future research efforts should include other oceanic-atmospheric processes such as the Pacific North American Index (PNA) and sea surface temperatures. Additionally, current SNOTEL data (April 1 SWE) was evaluated and a lead-time approach was adopted such that predictive information about SWE variability (as a result of oceanic-atmospheric variability) was provided. The use of the non-parametric rank-sum test removed assumptions of normality or linearity in oceanic-atmospheric and SWE relationships. While the coupling of interdecadal (PDO, AMO and NAO) variability identified several regions of interest, the authors recognize the short period of record (1941 to 2004) utilized in this evaluation. This limitation can be addressed in future research efforts by reconstructing

(using tree-ring chronologies) April 1 SWE, thus, providing an extended period of record.

[18] **Acknowledgment.** This research is supported by the Wyoming NASA Space Grant Consortium, the USGS Wyoming Water Research Program, the Wyoming Water Development Commission and the U.S. National Science Foundation award CMS-0239334.

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