Northern Annular Mode impact on spring climate in the western United States

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[1] Shifts in stormtrack position associated with the Northern Annular Mode (NAM) are linked to temperature changes and reduced spring precipitation in the western United States. During the transition to spring following a high-index winter, weakening of the stormtrack over the northeastern Pacific Ocean and western United States is shown to lead to warmer and drier conditions west of the Rocky Mountains and increased precipitation just east of the Rocky Mountains, consistent with observations of early spring onset in the western United States. Given projected increases in the average annular mode index and associated poleward shifts in the stormtrack, this analysis provides additional evidence that much of the western United States will experience more severe drought conditions over the next several decades, irrespective of changes in temperature, because of an earlier shift to warm-season circulation patterns. **Citation:** McAfee, S. A., and J. L. Russell (2008), Northern Annular Mode impact on spring climate in the western United States, *Geophys. Res. Lett.*, *35*, L17701, doi:10.1029/2008GL034828.

1. Introduction

[2] Cool-season precipitation plays a critical role in ecosystem [*Swetnam and Betancourt*, 1998] and hydrological processes [*Redmond and Koch*, 1991] in the western United States. Precipitation and temperature during the transition into spring have particularly important phenological impacts [*Schwartz and Reiter*, 2000], and some of the strongest trends in temperature, frost days and streamflow have been observed during the late winter and early spring [*Cayan et al.*, 2001; *Stewart et al.*, 2005]. Resource managers will need adequate projections of likely climate change during these seasons to optimize planning decisions. Despite their importance in terms of impact and the focus on identifying trends, the atmospheric dynamics of the transitional seasons have received little attention [*Fleming et al.*, 1987; *Abatzoglou and Redmond*, 2007].

[3] The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report projects decreasing cool-season precipitation south of about 40°N latitude [*Christensen et al.*, 2007], as do other studies [e.g., *Meehl et al.*, 2007; *Seager et al.*, 2007]. Given the frontal nature of winter precipitation, stormtrack position provides a good proxy for cool-season precipitation across the western United States at the synoptic scale [*Changnon et al.*, 1993; *Woodhouse*, 1997]. Models project a northward shift in stormtrack position [*Yin*, 2005; *Lorenz and DeWeaver*, 2007] that should be consistent with reduced precipitation in the western United States. While previous studies have examined the impact of these dynamics on annual averages or during mid-winter [e.g., *Meehl et al.*, 2007; *Seager et al.*, 2007, *Thompson and Wallace*, 1998], their impact during the transition into spring has not been thoroughly explored.

[4] The Northern Annular Mode (NAM) is the first empirical orthogonal function of sea level pressure poleward of 20°N, and the pattern extends vertically through the troposphere [*Thompson and Wallace*, 1998]. The positive phase of the NAM is characterized by an increase in the pressure gradient between the mid-latitudes and the pole [*Thompson and Wallace*, 1998]. High index values are commonly associated with poleward displacement and increased zonality of the stormtrack, low index values with a more southerly and meridional stormtrack pattern [*Thompson and Wallace*, 2001]. The JFM value of the NAM has previously been linked to increased temperature over much of the extratropics and to precipitation anomalies over the North Atlantic and Europe during the mid-winter [*Hurrell*, 1995; *Thompson and Wallace*, 2001]. The NAM has its greatest variance and coupling with the stratosphere between January and March (JFM) [*Thompson and Wallace*, 2000]. Thus, the JFM NAM index (Figure 1a) should provide a reasonable proxy for cool-season average stormtrack position.

[5] In this study we identify a quantifiable link between the NAM and precipitation over the western United States that appears to be unique to early spring (February to April). We confirm that the NAM provides a reasonable stormtrack index for the spring and demonstrate coherent relationships between the NAM, stormtrack position and geopotential height anomalies. Most significantly, we establish relationships between the mid-winter NAM and precipitation and temperature patterns across the western United States during the transition from winter into spring (February to April, FMA) that are consistent with the observed changes in atmospheric circulation.

2. Data and Methods

[6] Average JFM NAM index values were calculated from the National Weather Service Climate Prediction Center's (CPC) Arctic Oscillation monthly index (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html). The Arctic Oscillation index is commonly used to track the state of the NAM [*Thompson and Wallace*, 1998]. The stormtrack was calculated as a seasonal average of the monthly variance of the daily meridional component of wind at 300 hPa after application of a first-difference filter [*Quadrelli and Wallace*, 2002].

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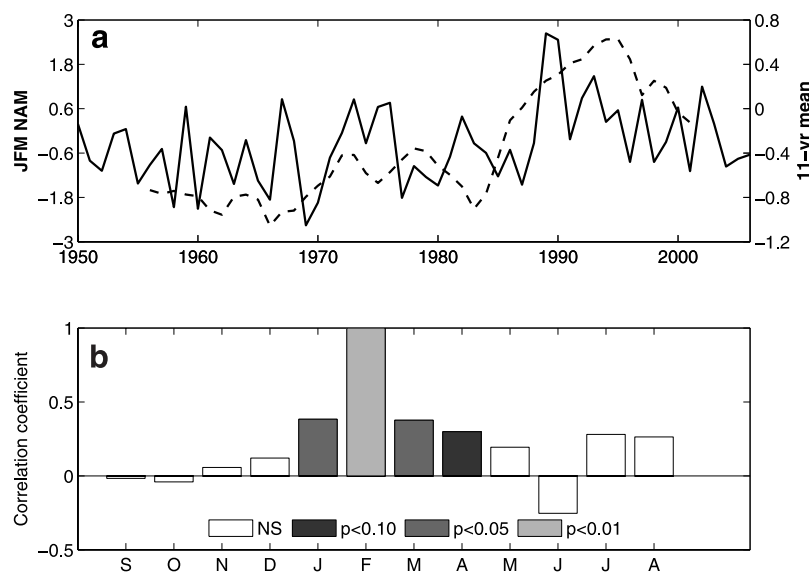
Figure 1. (a) Annual January to March (JFM) value of the Northern Annular Mode (http://www.cpc.ncep.noaa.gov/products/ precip/CWlink/daily_ao_index/ao_index.html), and (b) the monthly correlation with the February NAM, 1978–1998. White bars are not significant. Light, medium and dark shading indicates one-tailed significance at p < 0.01, p < 0.05, and p < 0.1.

Because of the general increase in stormtrack amplitude during high-index years [*Thompson and Wallace*, 2001], monthly grid cell values were normalized by the hemispheric average variance in meridional wind, emphasizing spatial differences in the stormtrack. Geopotential height anomalies at 500 hPa and 300-hPa meridional wind are derived from $2.5° \times 2.5°$ NCEP/NCAR reanalysis [*Kalnay et al.*, 1996]. Precipitation data are from the CPC Unified Precipitation $0.25° \times 0.25°$ observational data set [*Higgins et al.*, 2000], and temperature data is from the University of Delaware's $0.5° \times 0.5°$ observational record [*Willmott and Matsuura*, 1995]. All analyses were conducted over the period 1978– 1998.

[7] The spatial patterns of the relationships between the JFM NAM, stormtrack, geopotential height, precipitation and temperature were investigated using point correlations. The significance of correlations at individual points was tested against 10,000 synthetic time series. Between 1978 and 1998 the JFM NAM index approximates a gamma distribution and has a 1-year autocorrelation of 0.43. We analyzed the stability of the correlation patterns by splitting the data into odd and even years, re-analyzing each subsample, and comparing the sign – negative ($r \leq -0.05$), null ($-0.05 < r < 0.05$), or positive ($r \geq 0.05$)-of the correlation at each point.

3. Results

[8] In addition to the marked increase in the late-1980's (Figure 1a), the NAM displays monthly autocorrelation that persists further into the spring than the autumn (Figure 1b). The expected northward shift in the stormtrack should be associated with decreased precipitation across the western United States during the cool season and with regional temperature anomalies consistent with

the change in precipitation, although these have not previously been demonstrated.

[9] There is little NAM signature in 500-hPa height or stormtrack anomalies during the late autumn and early winter, October to December, (Figure 2a). By mid-winter, December through February, the classic high NAM index pattern does emerge, particularly over the northern Atlantic Ocean and Europe (Figure 2b). There are significant positive geopotential height anomalies in the mid-latitudes over northern Europe, eastern North America and the western and central Pacific Ocean, and significant negative anomalies near the pole and over Greenland. The stormtrack is shifted northward over much of the globe, typically just poleward of the positive geopotential height anomaly.

[10] By early spring, however, the pattern of anomalies becomes more complex. There are still a deep negative 500-hPa anomaly over Greenland and a mid-latitude positive anomaly over the Atlantic Ocean and Europe. The storm track is zonally shifted north over this region, as well (Figure 2c). However, the positive geopotential height anomaly over the Pacific shifts east and north leading to an east-west pressure gradient over western North America. The stormtrack anomaly also shifts north over the Pacific, placing the positive anomaly over the polar regions, with a significant weakening of the stormtrack over the eastern Pacific and western North America. This leads to an apparent fragmentation of the stormtrack.

[11] High-index winters are typically preceded by warmer than normal conditions over the Pacific Northwest (Figure 3a). Mid-winters are cool along the California coast, with few significant impacts elsewhere (Figure 3b). Springs following high-index winters however, are characterized by warm anomalies across much of the southwestern United States and northern New Mexico, with smaller areas of significant cool anomalies over portions of the Pacific Northwest and northern Rocky Mountains (Figure 3c).
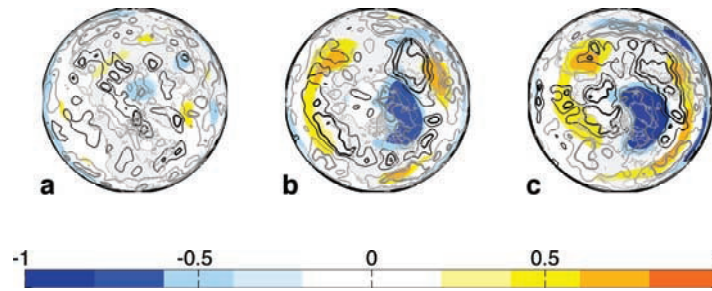
Figure 2. Correlation between the JFM NAM and monthly stormtrack and 500-hPa geopotential height for (a) October to December, (b) December to February and (c) February to April. Colors indicate correlations between the NAM and geopotential height significant at 90%. Black (gray) lines indicated positive (negative) correlations between the NAM and stormtrack. Bold lines indicate correlations significant at 90%.

[12] Autumns prior to high-index winters appear generally, but not significantly dry across the western United States, with regions of significant negative correlations over western Texas and Nebraska (Figure 3d). High-index winters themselves are unremarkable, with only small, scattered regions of significant correlations between DJF precipitation and the NAM index (Figure 3e). During the spring, however, an interesting pattern develops with dry conditions west of the Rocky Mountains, particularly in the Southwest, and wetter conditions over the Plains on the lee side of the Rocky Mountains (Figure 3f). These correlations are significant at 90% and do not change in sign with resampling.

[13] The main weaknesses in this argument are the restricted analysis period and the relatively weak statistical significance of the precipitation correlation. Limiting the analysis to the period of time since 1978 is necessary to detect the potential NAM impact given the increase in data quality and the current strong influence of the El Niño - Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) on the region's climate [Cayan et al., 1998]. Similar patterns are observed in the same analyses over the period 1955–1998 (not shown). Moreover, each of the analyses, based on independent data and reanalysis,

leads to the same answer. These considerations give us additional confidence in the results.

4. Discussion

[14] Given robust projections for increasing NAM index values over the 21st century [Yin, 2005; Miller et al., 2006] and observed northward shifts in the jet [Archer and Caldeira, 2008], it is important to determine the potential impacts of the NAM on regional climate patterns. For the first time, we have identified a link between the NAM and spring temperature and precipitation over the western United States. The most striking results from these analyses are that 1) they are internally and mechanistically consistent, 2) the greatest impact of the mid-winter NAM over the western United States actually occurs during the late winter and early spring, and 3) the stormtrack appears to fragment after high-index winters, developing an east/west break over North America.

[15] Although some of the relationships are not statistically significant at 95% or 99%, the basic patterns are robust to resampling and consistent with the observed changes in stormtrack position during the early spring. Each indicates that northward shifts in the mid-latitude stormtrack have
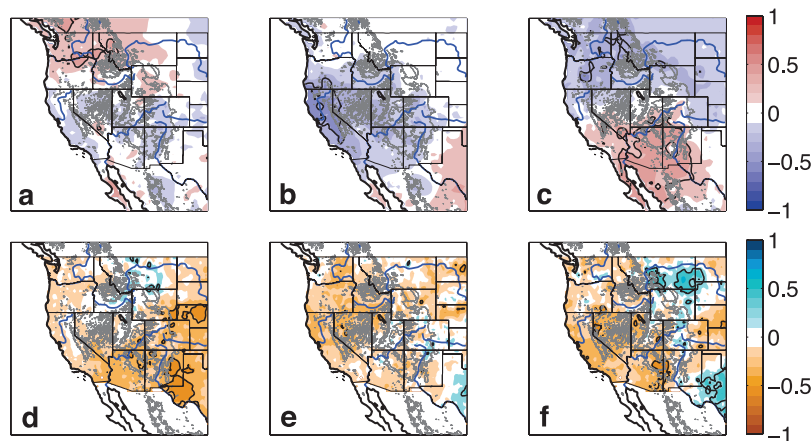

Figure 3. Correlation between the JFM NAM and (a–c) temperature and (d–f) precipitation over the western United States for October to December (Figures 3a and 3d), December to February (Figures 3b and 3e), and February to April (Figures 3c and 3f). Correlations significant at 90% are outlined in black. Heavy blue lines indicate major rivers; the 2000-m isohypse is indicated by fine gray lines.

manifest as decreases in precipitation over the western, particularly the southwestern, United States. The northward and eastward displacement in the stormtrack across western North America is mirrored in a reduction in precipitation west of the Rocky Mountains. The generally increasing trend in the NAM is also consistent with the stronger trend in spring than autumn surface temperatures [*Abatzoglou and Redmond*, 2007].

[16] Spring weather is critical in determining the phenology of ecological and hydrological events [*Schwartz and Reiter*, 2000; *Stewart et al.*, 2005]. Across the western United States, observed shifts in the position of the stormtrack, as indexed by the NAM, had the strongest impacts on temperature and precipitation in the spring. Autumn drying associated with the positive phase of the NAM is not consistent with observed stormtrack and geopotential height responses. The NAM had almost no discernable impact on mid-winter precipitation, despite the fact that the polar vortex is most strongly developed at that time. This may be due to aspects of the atmospheric dynamics during the spring, such as the northerly located and unstable jet [*Fleming et al.*, 1987].

[17] The expected response [*Thompson and Wallace*, 2001], and the one observed over the Pacific Ocean in the winter and over the Atlantic Ocean through the winter and spring, is a simple zonal shift in the position of the stormtrack accompanied by increased geopotential height over the mid-latitudes. Over the Pacific Ocean, however, the stormtrack appears to fragment during the tail end of high-index winters. The spring-time jet typically has an unstable position [*Fleming et al.*, 1987]. *Archer and Caldeira* [2008] note that one characteristic of summer (JJA) circulation is fragmentation of the Northern Hemisphere jet. Thus, one consequence of a high mid-winter NAM might be an earlier switch from cool- to warm-season circulation characteristics. Over much of the western United States, the transition from winter to summer is marked by a reduced frequency of frontal storm events [*Barry and Chorley*, 1998]. An earlier switch to summer-like circulation is consistent with the observed decrease in precipitation and increase in temperature over the Southwest. It also explains why many of the anomalies are short-lived. For example, the transition between the cool rainy season and the hot dry foresummer in the Southwest typically occurs between March and April [*Barry and Chorley*, 1998]. An earlier transition into warm-season circulation patterns shifts the season that March experiences, but not April. It also suggests that reduced precipitation in the West, particularly the Southwest, will be the result of a shorter rainy season - fewer storms, not a change in the character of storms.

[18] We expect that, given observed increases in average jet latitude [*Archer and Caldeira*, 2008], projections for a northward shift in the stormtrack [*Yin*, 2005; *Lorenz and DeWeaver*, 2007] and changes in ENSO's interaction with mid-latitude circulation [*Meehl et al.*, 2007], the NAM will have greater influence on the region's climate in the future. Projections of the NAM are considered robust because general circulation models (GCMs) simulate the historical spatial pattern of the NAM well and recreate many features of the temporal index, as demonstrated by *Shindell et al.* [1999]. If anything, GCMs underestimate the amplitude of

variability over time [*Miller et al.*, 2006]. Model results have suggested that a northward shift in the stormtrack associated with expansion of the Hadley cell will result in reduced winter precipitation over the southwestern United States [*Seager et al.*, 2007; *Seidel et al.*, 2008]. Whether the northward shift in the stormtrack is driven by the tropics, the extra-tropics, or the two acting in concert, it is likely to have the same result – a reduction in precipitation over western and particularly southwestern North America related to changes in the length of the rainy season. This observational study demonstrates that even the small northward displacements observed over the past 30 years are associated with reduced precipitation in the sub-tropics and increases our confidence in precipitation projections for the 21st century.

5. Conclusions

[19] The projected increase in the NAM [*Miller et al.*, 2006] and northward shift in the stormtrack [*Lorenz and DeWeaver*, 2007; *Yin*, 2005] may lead to reductions in late-winter and spring precipitation over the western United States, exacerbating drought associated with increases in surface temperature. The most striking results from these analyses are that they are consistent, both internally (despite using independently collected observational data and reanalysis) and with climate theory and coupled model projections, and they are also most pronounced during the spring. At least initially, the northward shift in the stormtrack may manifest as an earlier shift to warm-season circulation patterns. Given the presence of hydrological and ecological thresholds such as snowmelt and growing season onset during the spring and the significance of the phenology of those events, climate change during the spring may have more significant impacts than similar variations during the mid-winter or mid-summer.

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