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Asymmetry between trends in spring and autumn temperature and circulation regimes over western North America

J. T. Abatzoglou[1] and K. T. Redmond[1]

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[1] Observational evidence shows that spring temperatures over western North America have undergone significant warming over the past half century, while autumn temperatures have shown relatively little change. Low-frequency modes of atmospheric variability for spring and autumn are demonstrated to account for a great deal of the seasonal asymmetry, with trends in spring circulation patterns exacerbating regional warming, and trends in autumn circulation patterns counteracting warming. After excluding warming associated with the primary modes of atmospheric variability, temperature trends in spring and autumn over western North America are similar to one another and in broad agreement with seasonal trends from a multimodel ensemble. **Citation:** Abatzoglou, J. T., and K. T. Redmond (2007), Asymmetry between trends in spring and autumn temperature and circulation regimes over western North America, *Geophys. Res. Lett.*, *34*, L18808, doi:10.1029/2007GL030891.

1. Introduction

[2] Temperatures across western North America have seen a pronounced warming over the past 50 years [*Intergovernmental Panel on Climate Change*, 2007]. Warming temperatures have led to ecological and economic impacts with respect to the timing of hydrologic processes across much of the western US including an advance in the timing of snowmelt runoff and blooming of plants [*Cayan et al.*, 2001], a decrease in the fraction of precipitation falling as snow in the lower elevation sites of the Sierra Nevada and Pacific Northwest [*Knowles et al.*, 2006], and a decline in spring snow water equivalent in the mountains of western North America [*Mote*, 2006]. Collectively, the hydroclimatological response to the observed warming leads to heightened flood risks during winter and decreased streamflow in late spring and summer, both of which have implications for water management in the western US. In addition to the hydrologic impacts, warmer spring temperatures and an advance in the timing of snowmelt have been shown to set the stage for an earlier and prolonged fire season across the western US [*Westerling et al.*, 2006].

[3] In contrast, over the last half century autumn surface temperatures across western North America have not shown a statistically significant warming, hereafter referred to at the 95% level using the methodology of *Santer et al.* [2000]. Autumn (SON) mean temperatures for the 11 western states in the continental US as a whole (aggregated from divisional data produced by the National Climatic Data Center [NCDC]) have not exhibited statistically significant warming over the time period 1958–2006, whereas spring (MAM) temperatures have shown a statistically significant warming of +0.36°C/decade (Figure 1). We note that both winter and summer temperatures for the western US have exhibited significant positive trends of +0.26°C/decade and +0.16°C/decade, respectively. This paper explores the asymmetry in spring and autumn temperature trends over western North America to learn whether variations and trends in atmospheric circulation regimes during these transition seasons might help explain differences between the observed and modeled temperature trends.

[4] In order to better understand the origins of regional scale trends in temperature across western North America we consider how these trends are influenced by the observed changes in the dominant modes of atmospheric circulation. The atmosphere has many preferred low-frequency circulation modes including the Arctic Oscillation (AO) and the Pacific North American (PNA) pattern. Recent work has shown that observed trends over large sections of the Northern Hemisphere (NH) project strongly onto trends in natural circulation regimes. It is not presently clear what mechanisms are driving observed trends in circulation patterns; however, it remains possible that external forcing may be partially responsible for the observed trends [*Miller et al.*, 2006]. *Wu and Straus* [2004] showed that about half the warming trend over NH land areas during winter over the last half century is accounted for by a trend toward the positive polarity of the AO and PNA-like circulation modes. However, these studies have focused their attention on influence on the winter time circulation, while the important transition seasons of spring and fall have not been examined in detail.

[5] To obtain a better understanding of trends in regional-scale surface climate it is crucial to assess the nature of both short-term and long-term variability in circulation patterns. This is especially important given the climate trends anticipated due to direct forcing associated with increasing atmospheric concentrations of greenhouse gases. *Wu and Karoly* [2007] explored the influence of excluding warming associated with trends in the atmospheric circulation in the detection of regional scale warming trends over the last half of the 20th century. Upon removal of regional warming trends associated with the first three primary circulation modes, they concluded that the fraction of the globe that has observed significant warming trends on both annual and winter-mean time scales exceeds that which may be attributed to internal climate variability alone. In this study we apply a similar set of techniques to determine (1) what fraction of the observed trends in spring and autumn over western North America are associated with trends in circu-

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[1] Western Regional Climate Center/Desert Research Institute, Division of Atmospheric Science, Reno, Nevada, USA.

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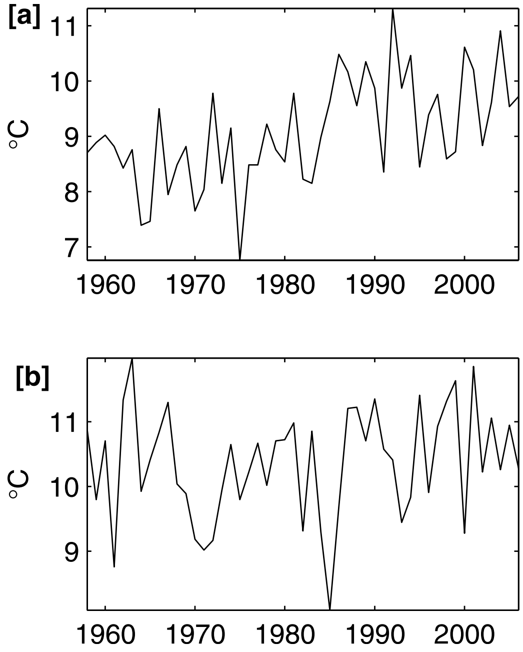

Figure 1. Time series of mean surface temperature from 1958–2006 for (a) spring, and (b) autumn areal averaged for the 11 westernmost states in the continental US (AZ, CA, CO, ID, MT, NV, NM, OR, UT, WA, WY), from NCDC's climate divisional data set.

lation regimes, (2) if the observed disparity between spring and autumn trends in temperature over the western US is associated with contrasting trends in circulation patterns during these seasons, and (3) if the observed residual trends (after excluding warming associated with circulation patterns) for spring and autumn are similar to one another and consistent with the ensemble mean multimodel response to historic 20th century external forcings.

2. Data and Methods

[6] Monthly surface air temperatures on a 5° horizontal resolution grid from 1958–2006 are taken from the NOAA merged land air and sea surface temperature data set. A separate measure of lower atmospheric temperature is taken using 1000–500 hPa geopotential thickness (proportional to the mean layer temperature) from the NCEP-NCAR reanalysis data set. Circulation patterns are evaluated using monthly 500 hPa geopotential heights from the reanalysis.

[7] Empirical orthogonal function (EOF) analysis is applied to monthly mean 500 hPa geopotential height anomalies north of 20°N. EOF patterns are calculated separately for spring and autumn. Although the computation of seasonal (3-month aggregate) EOF patterns from monthly data during these transition seasons may introduce problems due to changes in the basic state between early and late spring or autumn, the results are not significantly changed if we employ EOF patterns for each month separately. Area weighting is applied to the data set by multiplying the field by the square root of the cosine of latitude prior to computing the covariance matrix. The first four EOF patterns are retained in both spring and fall, accounting for 41% and 42% of the cumulative explained variance, respectively.

[8] We partition the observed temperature data set into linearly congruent and residual components with respect to the diagnosed monthly circulation modes as shown in equation (1). We first calculate regression coefficients, $\alpha_i(x, y)$, from the monthly temperature time series at each grid point with the first four principal components (PC) taken from 500 hPa geopotential height fields. The component of the temperature time series that projects onto the identified circulation modes (hereafter: circulation-derived component) is created through multiple linear regression of $\alpha_i(x, y)$ and their corresponding PCs. The component of the temperature data set not associated with the identified circulation patterns (hereafter: residual component) is obtained by subtracting the observed temperature from the circulation-derived temperature.

$$T(x,y,t) = \sum_{i=1}^{4} \alpha_i(x,y)^* PC_i(t) + \delta(x,y,t) \tag{1}$$

[9] This allows us to decompose the observed temperature time series into a circulation-derived component that projects onto the circulation indices (first term on RHS of equation (1)), and a residual component independent of circulation modes (second term on RHS of equation (1)). A least squares linear fit is applied to each of the three terms in equation (1) to calculate observed trends, circulation-derived trends, and residual trends in temperature. Observational results are compared to a multimodel ensemble run under the 20th century forcing from a set of three models (GFDL-CM2.1, NCAR-CCSM3, CCCMA-CGC3.1) used in the Fourth Assessment of the IPCC. The same methodology used to extract the circulation-derived and residual temperature from the observed data is followed for each of the model runs.

3. Results

[10] The circulation patterns taken from the EOF analysis are readily identified as an AO-like pattern, a PNA-like pattern, and variants that blend together the regional wintertime modes and the more zonally elongated summer modes [e.g., *Barnston and Livezey*, 1987]. The first EOF pattern in each season resembles an AO-like pattern with its strongest $\alpha_i(x, y)$ centered over the North Atlantic region, while the second EOF dominates over the Pacific sector and contributes 11.4% and 12.1% of the variance in spring and fall, respectively. Each of the four identified circulation modes are used to construct the circulation-derived temperature data set from equation (1), but for brevity we show EOF 2 for spring and fall in Figures 2a and 2b, respectively. Although these patterns have a slightly different spatial structure, they are both PNA-like with a similar regional signature over the North Pacific-western North America region. The associated $\alpha_i(x, y)$ for both modes consists of positive temperature anomalies over western and northern North America and negative anomalies over the mid Pacific akin to the cold ocean-warm land pattern of *Wu and Straus* [2004] (Figures 2e and 2f). However, the seasonally averaged time series of these modes are quite different between

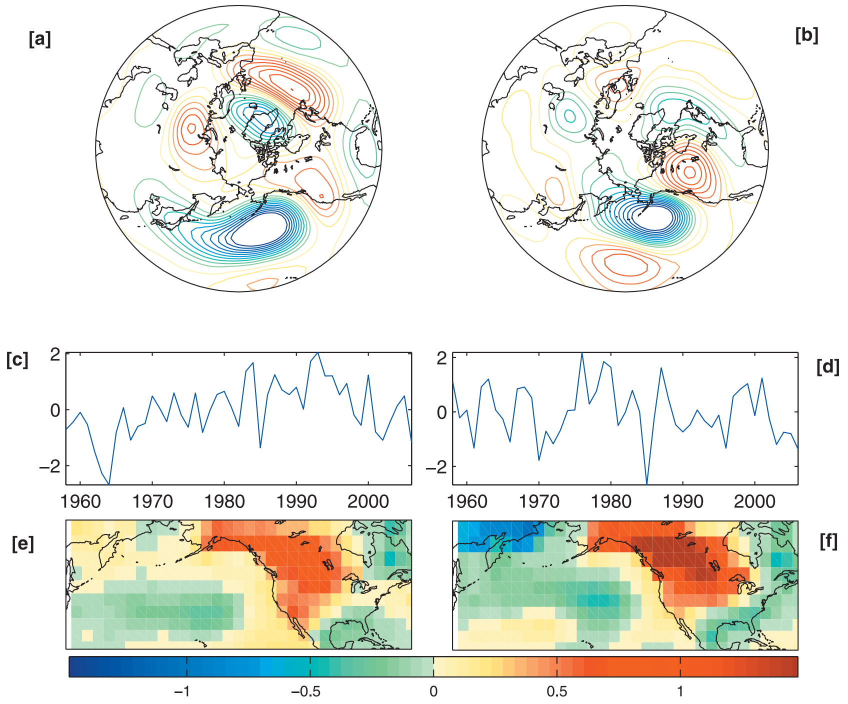

Figure 2. Second EOF of 500 hPa monthly mean geopotential height for (a) spring, and (b) autumn, (c, d) their respective associated seasonal averaged PC, and (e, f) their respective regression coefficients with monthly mean surface temperature.

spring and autumn, with spring showing a robust positive trend up until the early 1990s, and the autumn showing a non-significant negative trend (Figures 2c and 2d). Calculated trends in the 700 hPa wind vector (trends are equivalent barotropic in the extratropical troposphere) for spring show an enhanced cyclonic flow over the North Pacific in agreement with the observed trend toward the positive polarity of the PNA-like pattern, a deeper Aleutian low, and an enhanced southerly flow that delivers relatively warm air to the west coast of North America (auxiliary material Figure S1a[1]). Conversely, the autumn trend, albeit not significant, in the 700 hPa wind vector is of opposite sign over the region, depicting a trend toward a more northerly flow that advects cooler air along the west coast of North America (auxiliary material Figure S1b).

[11] Linear trends in observed surface temperature for both spring and autumn are shown in Figures 3a and 3b, respectively. Both seasons show a broad majority of positive temperature trends across the domain, with the most robust warming trends at high latitudes and over land. However, the observed trends are rather different over the North Pacific and western North America between spring and autumn. In spring there are strong positive trends over western North America and negative trends over the North Pacific, whereas in autumn there are neutral or weakly positive trends over western North America and positive trends over the North Pacific. The areally-averaged trend over western North America (32.5–52.5°N, 110–125°W) for spring is statistically significant at +0.28°C/decade; by contrast, for autumn the trend is not statistically significant (Table 1).

[12] The component of the trend associated with the identified EOF patterns in spring and autumn shows opposing contributions over western and northern North America, with the trends in spring circulation modes projecting a warming signal over the region, and conversely the trends in autumn circulation modes projecting a cooling signal over the region (Figures 3c and 3d). The asymmetry in circulation-derived temperature trends is strong across the western US, but is most pronounced in British Columbia and southeastern Alaska. Trends in the lower atmospheric temperature derived from 1000–500 hPa thickness fields (not shown), show a similar pattern with a strong circulation-derived warming signal over western North America and nearly an equal component of cooling over the North Pacific. Similar to the results obtained from the surface temperature data set, trends of circulation-derived lower atmospheric temperature in autumn show an opposing, and weaker, pattern from those in spring.

[13] Upon removal of the temperature signal linearly congruent with the identified circulation patterns, the trends calculated from the residuals become quite similar between spring and autumn across western North America. Time series of the observed, circulation-derived, and residual spring areal averaged surface temperature are shown in auxiliary material Figures S2a, S2c, and S2e, respectively. Time series for fall are shown in auxiliary material Figures S2b, S2d, and S2f. Analogous time series for 1000–500 hPa geopotential thickness are shown in auxiliary material Figure S3. Residual spring trends are substantially reduced to +0.17°C/decade, while autumn trends are increased to +0.12°C/decade (Table 1). Although the residual surface temperature trend for autumn is not statistically significant, trends calculated from thickness over the same domain do become statistically significant upon excluding the circulation-derived tempera-

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL030891.

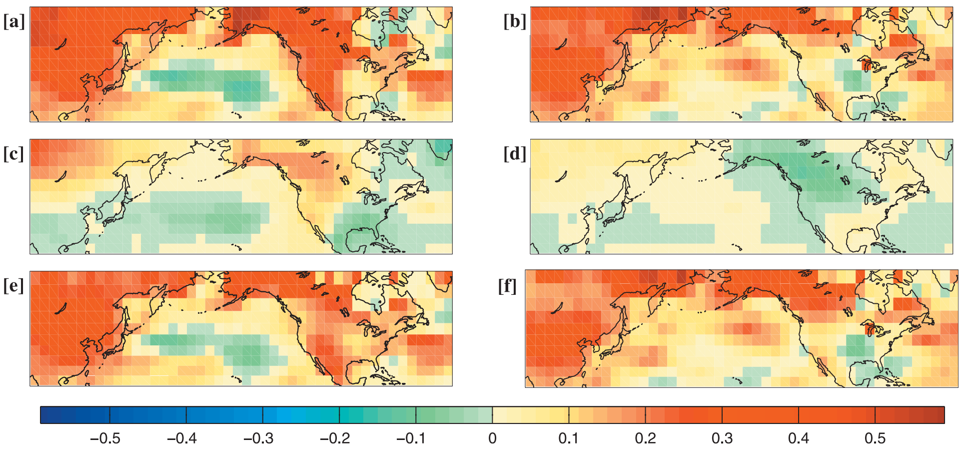

Figure 3. Linear trend in MAM for (a) observed surface temperature, (c) surface temperatures associated with the first four EOF patterns, and (e) residual surface temperature over the time period 1958–2006. (b, d, f) Trends for SON. Trends shown are in units °C/decade.

ture signature. Trends in spring temperature exceed those in autumn even after the circulation-derived temperature signal is removed. From a purely radiation based perspective there are physical reasons why spring warming trends may exceed autumn trends. Snow albedo feedback across much of the mountainous West is likely to be influential as warmer temperatures in winter and spring lead to decreased snow cover that in turn alters albedo and outgoing longwave radiation to exacerbate increases in spring warming. *Groisman et al.* [1994] suggest that such feedback processes can account for up to half of the observed trend in spring warming over extratropical NH land over the last two decades of the 20th century. Conversely, snow-albedo feedback is likely to be rather minimal during the early stages of the snow accumulation season in autumn. In autumn, changes in land cover, particularly increased areal coverage of irrigated lands across parts of the West have been shown to dramatically alter the ratio of sensible to latent heating during the climatologically dry fall season in the western US, thereby leading to cooling at the surface [*Kueppers et al.*, 2007].

[14] The multimodel ensemble run under the late 20th century forcing scenario shows warming of equal magnitude during spring and autumn over western North America with trends of +0.17°C/decade and +0.2°C/decade, respectively. The model runs examined failed to show any notable trend in circulation modes in spring or fall, and the multimodel residual trends remain relatively unchanged after we exclude the circulation derived temperature signal (see Table 1). Although models simulate many of the same preferred atmospheric circulation modes as in the real atmosphere, the amplitude of trends (e.g., in the AO and PNA) is underestimated [*Miller et al.*, 2006].

4. Conclusions

[15] Atmospheric circulation patterns are shown to account for up to 40% of the springtime warming observed over western North America during the past half century. Positive trends in the AO and PNA-like patterns during spring have led to enhanced poleward-directed flow along the West Coast and the advection of warmer maritime air over the continent. Conversely, opposing trends in circulation regimes during autumn have likely acted to mask the regional detection of anthropogenic warming over western North America. After removing the circulation-derived temperature signal associated with the first four EOF patterns during spring and autumn we find trends over western North America to be similar between these transition seasons and consistent with the multimodel ensemble.

[16] In order to better establish if there is a detectable regional surface temperature signal attributable to an enhanced greenhouse effect, it is critical to discern other sources of climate variability that may influence regional climate. In the same manner that synoptic conditions influence the spatial expression of surface temperature on daily timescales, low-frequency modes of variability influence surface temperatures on longer timescales. Our analysis shows that atmospheric regimes have exhibited significant trends over the period of record, in an opposing manner between spring and autumn, thereby leading to dramatically different seasonal trends in surface temperature. By accounting for variability and trends in surface temperature that are associated with atmospheric circulation regimes, we may be in a better position to answer many of the questions regarding climate change detection.

[17] It is presently not clear as to what is responsible for the contrasting seasonal trends in circulation regimes over the North Pacific-western North America region over the last half century. Although spring and autumn are both transition seasons, they are by no means similar with respect

Table 1. Trends in Surface Air Temperature (SAT) and 1000–500 hPa Geopotential Thickness Areal Averaged Over the Domain 32.5°N–52.5°N, 110°W–125°W[a]

Variable	MAM	SON
SAT original	**+0.28 (+0.17)**	+0.07 (**+0.20**)
SAT residual	**+0.17 (+0.16)**	+0.12 (**+0.19**)
Thickness original	**+7.1**	+2.4
Thickness residual	**+4.3**	**+3.3**

[a] Trends calculated for the time period 1958–2006 are in °C/decade and meters/decade for SAT and geopotential thickness, respectively. The multimodel ensemble trends (1960–1999) are shown in parentheses. Statistical significance is denoted in bold.

to atmospheric dynamics. For example, the jet over the Pacific is displaced more than 5° poleward in autumn than in spring [*Abatzoglou and Magnusdottir*, 2006]. If, for example, trends in circulation regimes during spring were associated with trends in boundary forcing (e.g., sea surface temperatures [SST]) it is possible that differences in the latitudinal position of the jet may mediate seasonal differences in trend behavior in the extratropical circulation [*Peng et al.*, 1997].

[18] It appears most likely that the observed spring versus autumn differences in atmospheric circulation pertain to seasonal differences in extratropical air-sea interactions. The persistence (associated with a deep mixed layer) of dominant winter SST regimes provides for enhanced air-sea coupling during spring, while autumn circulation is less coupled to dominant wintertime SST modes or trends until late autumn or early winter. The relation between SST and the warming of spring temperatures in western North America has been noted by *Stewart et al.* [2005] who associate a fraction of the spring warming trend with the Pacific Decadal Oscillation. We confirm that SST trends in spring and autumn are indeed quite different over the North Pacific basin (not shown), and further work is needed to sort out both the mechanisms responsible for the observed differences in SST trends and their respective influence on circulation patterns. Though the documented modes of variability are comprised of natural atmospheric regimes, modeling results have suggested that external forcing will likely alter not only the mean atmospheric state, but also the frequency and polarity of circulation regimes [*Palmer*, 1999]. Further work is needed to understand what is responsible for the contrasting trends in circulation in spring and autumn, and whether the asymmetry in these seasonal trends are a forced response to climate change or within the realm of natural variability.

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References

Abatzoglou, J. T., and G. Magnusdottir (2006), Planetary wave breaking and nonlinear reflection: Seasonal cycle and interannual variability, *J. Clim.*, *19*, 6139–6152.

Barnston, A. G., and R. E. Livezey (1987), Classification, seasonality and persistence of low-frequency atmospheric circulation patterns, *Mon. Weather Rev.*, *115*, 1083–1126.

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson (2001), Changes in the onset of spring in the western United States, *Bull. Am. Meteorol. Soc.*, *82*, 399–416.

Groisman, P. Y., T. R. Karl, and R. W. Knight (1994), Observed impact of snow cover on the heat balance and the rise of continental spring temperatures, *Science*, *263*, 198–200.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., 996 pp., Cambridge Univ. Press, New York.

Knowles, N., M. D. Dettinger, and D. R. Cayan (2006), Trends in snowfall versus rainfall for the western United States, *J. Clim.*, *19*, 4545–4554.

Kueppers, L. M., M. A. Synder, and L. C. Sloan (2007), Irrigation cooling effect: Regional climate forcing by land-use change, *Geophys. Res. Lett.*, *34*, L03703, doi:10.1029/2006GL028679.

Miller, R. L., G. A. Schmidt, and D. T. Shindell (2006), Forced annular variations in the 20th century Intergovernmental Panel on Climate Change Fourth Assessment Report models, *J. Geophys. Res.*, *111*, D18101, doi:10.1029/2005JD006323.

Mote, P. W. (2006), Climate-driven variability and trends in mountain snowpack in western North America, *J. Clim.*, *19*, 6209–6220.

Palmer, T. N. (1999), A nonlinear dynamical perspective on climate prediction, *J. Clim.*, *12*, 575–591.

Peng, S., W. A. Robinson, and M. P. Hoerling (1997), The modeled atmospheric response to midlatitude SST anomalies and its dependence on background circulation states, *J. Clim.*, *10*, 971–987.

Santer, B. D., T. M. L. Wigley, J. S. Boyle, D. J. Gaffen, J. J. Hnilo, D. Nychka, D. E. Parker, and K. E. Taylor (2000), Statistical significance of trend differences in layer-average temperature time series, *J. Geophys. Res.*, *105*, 7337–7356.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger (2005), Changes toward earlier streamflow timing across western North America, *J. Clim.*, *18*, 1136–1155.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam (2006), Warming and earlier spring increases western U.S. forest wildfire activity, *Science*, *313*, 940–943.

Wu, Q., and D. J. Karoly (2007), Implications of changes in atmospheric circulation on the detection of regional surface air temperature trends, *Geophys. Res. Lett.*, *34*, L08703, doi:10.1029/2006GL028502.

Wu, Q., and D. M. Straus (2004), AO, COWL, and observed climate trends, *J. Clim.*, *17*, 2139–2156.

J. T. Abatzoglou and K. T. Redmond, Western Regional Climate Center/Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA. (john.abatzoglou@dri.edu)