The Magnitude of Decadal and Multidecadal Variability in North American Precipitation*

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Abstract

The authors use singular spectrum analysis to investigate the relative magnitude of decadal to multidecadal (D2M) variability in annual and seasonal precipitation anomalies across North America. In most places, decadal (10–20 yr) or multidecadal (20–50 yr) variability makes up less than 10% of the total variance in either annual or seasonal precipitation, with interannual variability or secular trends having much greater importance. Decadal variability is most prominent (contributing 25%–30% of the total variance) in Minnesota and northern California during winter, and the central Rocky Mountains in autumn. Eastern Québec is the only major region where precipitation exhibits significant variance in the multidecadal band. Precipitation across much of Canada exhibits significant variance at extremely low frequencies (greater than 50 yr), but variability at these time scales cannot be separated from secular trends because of the limited length of instrumental climate records. Decadal signals in the discharge of the Sacramento River and, to a lesser degree, the Colorado River are coherent and in phase with similar signals in regional precipitation. Prominent D2M signals do not resemble the low-frequency components of major climate modes such as ENSO or the PDO, which suggests that this behavior is not a product of a simple linear translation of a single climate forcing.

1. Introduction

Recent studies have suggested that the risk of drought over North America changes at time scales of one to several decades, and that these changes are linked to variations in ocean temperatures. Enfield et al. (2001) found that summer rainfall in the continental United States is correlated with the Atlantic multidecadal oscillation (AMO), with less rain falling during the warm phase of the AMO. Similarly, McCabe et al. (2004) demonstrated that multidecadal drought frequency is spatially coherent over the United States, and that the frequency and spatial pattern of drought is affected by the state of the AMO and the Pacific decadal oscillation (PDO). Understanding these long-term changes in drought, and their causes, may lead to improved climate predictions and drought risk outlooks with lead times of one or two decades (Sutton and Hodson 2005; McCabe and Palecki 2006).

In this paper, we investigate the relative magnitude of decadal to multidecadal (D2M) variability in precipitation across North America using a set of gridded instrumental precipitation records. Most prior studies of D2M variability in instrumental records of drought or precipitation have focused on identifying spatially coherent patterns and used data processed to emphasize variations at those time scales (e.g., Enfield et al. 2001; McCabe et al. 2004; McCabe and Palecki 2006). We adopt a complimentary approach that compares the amount of variance in decadal and multidecadal bands relative to the total variance at all time scales. Our study builds upon work done by Cayan et al. (1998), who described decadal variability in annual precipitation over western North America using a combination of bandpass filtering
and empirical orthogonal function analysis. Our contribution extends this analysis to include most of North America and benefits from the addition of nearly another decade of observations. By identifying where and when these signals are strongest, we highlight those regions that might benefit most from improved predictions of decadal and multidecadal behavior in the climate system. Moreover, in estimating the strength of D2M variability in instrumental records, we provide a baseline to compare low-frequency signals identified in longer precipitation records derived from proxy evidence (e.g., Gray et al. 2003; Hidalgo 2004).

2. North American precipitation in the frequency domain

We used regional precipitation data from the University of East Anglia Climatic Research Unit’s TS 2.1 0.5° × 0.5° gridded dataset of monthly climate observations (Mitchell and Jones 2005). The TS 2.1 precipitation data are interpolated from terrestrial surface meteorological stations and are continuous over the period 1901–2002. Data were obtained for the North American sector (24°–60°N, 50°–150°W), averaged to 1° × 1° resolution, and summed to create annual (October–September) and seasonal [December–February (DJF), March–May (MAM), June–August (JJA), September–November (SON)] totals. The gridded data were then smoothed with a 3° × 3° Gaussian filter to reduce spatial noise. Because data for northern Canada are derived from a sparse network of stations (New et al. 1999, 2000), with few stations operating before the 1960s, we emphasize that our results for that part of the domain should be regarded with caution.

Our choice of bands was based on zonally averaged spectral estimates of annual precipitation obtained using the multitaper method (MTM) (Thomson 1982). The MTM results (Fig. 1) indicated that the dominant time scales of precipitation vary with latitude: 2–7-yr variability is strongest south of 40°N, variability between 10 and 20 yr is greatest in the mid- and high latitudes, and variance above 20 yr is most prominent north of 50°N. There are also local variance minima between 7 to 10 yr at lower latitudes and between 18 to 20 yr at mid- and high latitudes. Based on these results, we separated variability into four bands: interannual (2–10 yr), decadal (10–20 yr), multidecadal (20–50 yr), and secular (greater than 50 yr). Applying the multitaper method, singular value decomposition (MTM-SVD; Mann and Park 1999) showed a concentration of spectral power (local fractional variance) between 10 and 20 yr (Fig. S1 in the supplemental material), which confirmed that decadal and multidecadal signals are distinct components of low-frequency variability in precipitation. The upper limit of our multidecadal band was constrained by the spectral resolution of MTM. With 100 yr of data and a time bandwidth parameter set to two, the method cannot distinguish signals with periods greater than 50 yr from variability associated with long-term trends (Mann and Lees 1996).

At each grid point, we subtracted the temporal mean to convert annual and seasonal precipitation records to anomalies and applied singular spectrum analysis (SSA) to decompose each series into interannual, decadal, multidecadal, and secular components (Fig. 2). SSA is a nonparametric method that performs singular value decomposition on the autocovariance matrix of a single time series using a specified lag window (M) to develop an orthogonal set of basis vectors (Vautard and Ghil 1989; Ghil et al. 2002). The original time series is then decomposed into M reconstructed components (RCs) and M corresponding normalized eigenvalues. Each RC shows the phase and amplitude of a signal over time, and its normalized eigenvalue measures the fraction of total variance contributed by that signal. We used an M of 15 yr but found our results to be stable for a range of values between 10 and 35 yr. Only the first six RCs were retained for analysis, as higher-order components produced by SSA often describe noise (Ghil et al. 2002). We estimated the dominant periodicity of each RC using the Fourier transform, and expressed the cumulative variance of the leading RCs within each band as a percentage of the total variance in annual or seasonal precipitation. We also applied SSA to naturalized streamflow records acquired from the California Department of Water Resources (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST) and the United States Bureau of Reclamation (J. Prairie 2006, personal communication).

We tested the local significance of D2M signals by comparing the percent variance in each band against the “expected” percent variance derived from a Monte Carlo analysis of 10 000 white noise time series the same length as the precipitation records. Regions where precipitation
displays more variance in a given band than white noise (at the 95% confidence limit) were identified as decadal or multidecadal “hot spots.” We also tested the field significance of each variance map using a bootstrap approach similar to Mann and Park (1999). During each realization, we reordered the time sequence of the grid-ded precipitation records, which preserves the spatial correlation structure of the data but destroys any time-evolution information. Next, we calculate the number of grid points that have more variance in each band than the limits derived from our local significance tests. We repeated the bootstrap procedure 1000 times to estimate the number of grid points expected to exhibit a significant fraction of total variance within a given band due solely to random chance.

3. Results

a. D2M variability in North American precipitation anomalies

Our results indicate that D2M variability is a relatively small component of precipitation over most of North America. For most grid points, low-frequency variability in either annual or seasonal precipitation contributes less than 10% of the total variance, with interannual variability or secular trends having much greater importance (Fig. 3; Fig. S2 in the supplemental material). Throughout most of the domain, annual precipitation does not contain significant decadal variability. The only exceptions are located in northern Canada (Labrador and northern Alberta), but these may be artifacts caused by the poor
spatial coverage and short length of observations in these regions. In contrast, decadal variability in seasonal precipitation can be quite prominent, at least for select areas. In Minnesota, northern California, and southern Oregon between one-quarter and one-third of the variance in winter precipitation falls within the decadal band. Decadal variability is also high during autumn over the central Rocky Mountains in Utah, Wyoming, and Colorado. Except in a few small areas, it is not a major component of spring or summer precipitation. We found high multidecadal variability over a large part of eastern Québec, where it contributes more than one-third of the variance in annual precipitation and is present in three of the four seasons. Significant multidecadal variability was also identified in both summer and winter precipitation for a small area in central and western Kansas. None of the decadal or multidecadal maps have a sufficient number of grid points with significant D2M variability to satisfy the field significance tests. Extremely low-frequency behavior (above 50 yr) is significant across much of Canada.

Fig. 3. Percent variance in (top to bottom) annual and seasonal precipitation at (left) decadal (10–20 yr), (middle) multidecadal (20–50 yr), and (right) secular bands (>50 yr). The red lines show regions where variability in each band exceeds the 95% significance level determined by applying SSA to 10 000 white noise time series the same length as the precipitation record. Local significance levels determined using a bootstrap procedure yielded very similar results. Maps that passed field significance tests at the 95% level are marked with an X in the lower-right corner.
(especially northern Canada) but, as noted earlier, variability at these time scales cannot be reliably separated from trend within only 100 yr of record. Much of this variance is concentrated at time scales greater than 75 yr and likely reflects the observed increase in precipitation across Canada during the twentieth century (Zhang et al. 2000).

Our results were largely insensitive to changes in the spatial resolution of the precipitation dataset, or the width of variance bands. Conducting SSA on station data (Fig. S3 in the supplemental material) or increasing the size of the spatial filter (Fig. S4 in the supplemental material) did not markedly change the proportion of variance in the decadal bands or alter the size or location of D2M hot spots. Using a much broader definition of decadal and multidecadal behavior (combining all variance between 8 and 75 yr) actually eliminated many of the hot spots identified using the narrower bands (Fig. S5 in the supplemental material) by elevating the noise floor established by our Monte Carlo procedure.

b. Decadal hot spots

We have identified four major regions in North America where precipitation exhibits significant decadal or multidecadal variability: Minnesota, northern California, the central Rocky Mountains, and eastern Québec. We illustrate the evolution of these signals during the twentieth century by averaging precipitation over each region, conducting SSA on each regional series, and examining the dominant reconstructed components (either the first RC or the sum of RC1 and RC2). In these regions, the dominant mode of variability is either decadal or multidecadal (Fig. 4). Winter precipitation in northern California varies with a period of roughly 14–15 yr. This signal, which is equivalent to the California pattern identified by Cayan et al. (1998), appears to have strengthened in the last decade and had its highest amplitudes around 1990 (dry) and the late 1990s (wet). It was also absent prior to 1930. The decadal component of autumn precipitation over the central Rocky Mountains operates on a 12–14-yr time scale. Over the last 40 yr, this component has been roughly in phase with the northern California pattern but this correspondence was not present before 1960. The decadal signal in winter precipitation in Minnesota has a 15–16-yr time scale and was strongest in the middle of the twentieth century. Eastern Québec has a period of roughly 33 yr, and shows prolonged dry conditions in the 1920s, the 1950s, and, to a lesser degree, the late 1980s and early 1990s.

The northern California and central Rocky Mountain hot spots largely overlap with the runoff-generating regions for the Sacramento River and Colorado River, respectively. Applying SSA to naturalized flow records for these two rivers suggests that decadal variability in streamflow may be driven, at least in part, by similar changes in seasonal precipitation. One-quarter of the variance in the annual flow of the Sacramento River is contributed by decadal signals, and this behavior has the same period and timing as the decadal mode in northern California winter precipitation (Fig. 5a). As with northern California precipitation, the decadal mode in streamflow was weak in the early part of the record and increased in amplitude over the twentieth century. This signal may also influence geomorphic activity in northern California, as levee breaks in the Sacramento–San Joaquin River (Florsheim and Dettinger 2007) have not occurred during troughs in the decadal component of precipitation and streamflow (Fig. 5a). The Colorado River flow record also has a decadal mode as its dominant signal (Fig. 5b), but the signal is weaker (roughly 11% of the total variance) and operates on a slightly shorter (11 yr) time scale. This mode appears to have strengthened after 1970. The
decadal signals in streamflow and precipitation series for the Rocky Mountain region operated independently of each other during the first half of the record but appear to have converged after roughly 1960.

4. Discussion

Our findings indicate that, over most of North America, D2M variability in precipitation is small relative to interannual variability and secular trends. Our estimates are lower than those of Cayan et al. (1998), who reported that decadal fluctuations account for 20%–45% of the total variance in precipitation over most of western North America. Although the earlier study used a broad definition of decadal variability (periods of 7 yr and greater), we separate lower-frequency variability into three distinct time scales and, as a result, report a lower proportion of the total variance in each category. We argue that splitting low-frequency variability into separate decadal and multidecadal bands is appropriate because these bands appear to have distinct spatial fingerprints (there is little overlap between our decadal and multidecadal hot spots), and because annual precipitation across North America exhibits a relatively narrow peak within the 10–20-yr band (Fig. S1 in the supplemental material).

It is clear that, with only 100 yr of data, D2M variability must be quite prominent (comprising almost a quarter of the total variance) to be detected above the noise floor. It may be that low-frequency signals in precipitation are widespread across North America but are too weak (or too low frequency) to be resolved within the relatively short instrumental record. More subtle D2M signals might be detected if this analysis was repeated using data that span a longer interval (precipitation estimates derived from tree rings, for example). It also seems likely that the strength of D2M variability in precipitation varies through time. Gray et al. (2003) reported that moisture-sensitive tree-ring records from sites in the central and southern Rocky Mountains contained significant variance at frequencies between 30 and 70 yr. Although these multidecadal signals were shown to remain stable for several centuries, there were also prolonged intervals (100–300 yr) where these signals either changed in frequency or were nonsignificant. With the exception of tree-ring sites in the southern Rocky Mountains (which fall within our central Rocky Mountain hot spot), the records examined by Gray et al. did not exhibit significant decadal or multidecadal variability during the twentieth century.

D2M signals in precipitation are prominent in select regions, where they contribute between one-quarter and one-third the total variance in annual or seasonal precipitation. Two of these regions include the watersheds of two of the most important rivers in the United States, and our results suggest that at least some of the decadal-scale variance observed in river discharge is caused by
similar long-term variability in regional precipitation. The close correspondence in northern California between precipitation and hydrology is a reflection of the local importance of winter precipitation (60% of the annual total arrives in winter). The weaker association between decadal precipitation and streamflow in the central Rocky Mountains most likely exists because that region receives a much smaller fraction of its annual precipitation during autumn, the season that actually exhibits low-frequency behavior. The Colorado River example also demonstrates that precipitation and discharge within the same area do not always exhibit the same long-term variability. Even though autumn precipitation over the central Rockies has some of the highest decadal variability in North America, those decadal signals have had, at most, a modest influence on Colorado River streamflow for most of the twentieth century.

Do the decadal hot spots identified here arise from deterministic and potentially predictable elements of the climate system? We have shown that where D2M variability in precipitation is strong, this behavior constitutes a large fraction of the total variance in annual or seasonal precipitation and has a clear impact on regional hydrology. However, our field significance tests indicate we cannot rule out the possibility that these regions are highlighted because of chance concentrations of D2M variance arising from processes that are spatially correlated but have an underlying white spectra. With the exception of the recent synchronicity in northern California and the central Rockies, D2M variability in these four regions is not coherent and varies over different time scales. This lack of agreement implies that these decadal or multidecadal signals in precipitation are not simply the result of a linear response to a single decadal mechanism. Moreover, the regions where precipitation is strongly decadal or multidecadal do not exhibit consistent teleconnections with major climate modes. For example, the positive phase of the Pacific decadal oscillation coincides with anomalously dry winters in western Canada and the Pacific Northwest and anomalously wet winters in Mexico and the southwestern United States (Mantua and Hare 2002). However, the most prominent decadal hot spots in winter precipitation are located between the two poles of the PDO response (Fig. 6). As noted by Florsheim and Dettinger (2007), northern California is located near the null (no consistent precipitation response) region of PDO teleconnections, as are the central Rocky Mountains. Winter precipitation in Minnesota is likewise not strongly correlated with the PDO index. None of the decadal or multidecadal signals derived from the four hot spots show a significant correlation with indices describing major climate modes such as ENSO, the PDO, or AMO (Table S1 in the supplemental material).

For three of the four hot spots, D2M variability in precipitation shows very little correspondence with sea surface temperatures (SST) (Fig. S6 in the supplemental material). The decadal signal in northern California is correlated with SST in the central North Pacific.
(positively) and central North Atlantic (negatively), but these connections are relatively modest and are significant over a very small portion of the SST field. Neither the decadal component in the central Rockies nor the multidecadal signal in central Québec shows any significant correlation with SSTs. In contrast, the decadal component of winter precipitation in Minnesota is significantly correlated with conditions in the North Pacific. Warm water in the central North Pacific and cold water off the western coast of North America (at approximately 50°N) coincide with enhanced meridional flow across the northern United States, which may act to steer winter storm systems toward Minnesota.

5. Conclusions

Our results demonstrate that the strength of low-frequency signals in time series describing precipitation anomalies varies considerably across North America. In most places, decadal or multidecadal variability is a modest component of precipitation and is small compared to the contribution from interannual variability or secular trends. However, D2M signals are quite strong in select regions. In northern California, the central Rockies, Minnesota, and eastern Québec, decadal or multidecadal variability makes up between one-quarter and one-third of the total variance in annual or seasonal precipitation. The decadal signals identified in northern California and the central Rockies appear to propagate into local hydrology and are associated with similar low-frequency signals in the discharge of the Sacramento and Colorado Rivers. Strong D2M behavior may also influence the risk of natural hazards, as evidenced by the absence of levee failures in the Sacramento–San Joaquin River system during persistent dry intervals.

Although D2M variability has clearly been a major element of the regional hydroclimate for select places in North America, important aspects of this behavior are uncertain. At present, we do not understand why decadal or multidecadal variability in precipitation is strong in some regions and weak in others. Because strong D2M signals in precipitation are, for the most part, not coherent between regions, it does not appear likely that they are forced by a single common factor. The fact that prominent D2M signals do not resemble the low-frequency components of major climate modes such as ENSO or the PDO suggests that this behavior is also not a product of a simple linear translation of a single climate forcing. It may be that strong D2M variability is the result of the interactions of two or more of these modes, or that it is produced by another aspect of the climate system not considered in our analysis. In addition, our results and the analysis of proxy records derived from tree rings (Gray et al. 2003) hint that low-frequency components of precipitation may not be stable through time. This observation should be tested in more locations across North America, especially those regions where precipitation exhibited high D2M variability during the twentieth century. It would also be instructive to evaluate the ability of models and proxies to reproduce the decadal or multidecadal component of North American precipitation described by observations.

Finally, we emphasize that precipitation deficits are only one aspect of the interactions between the climate system and the land surface that lead to the establishment and persistence of severe drought (Schubert et al. 2008). It is possible that D2M signals in other aspects of the climate system (e.g., summer temperature) or amplification of weak D2M signals in precipitation by landscape changes could create large changes in drought severity (described by, for example, Palmer drought severity index records) on decadal or multidecadal time scales. Hydrological storage may also serve to amplify D2M variability; Klemes (2000) noted that river discharge or lake level records “have a tendency to exhibit more pronounced and smoother cycles” (i.e., they have more D2M variability) than precipitation series because of carry-over effects caused by storage. However, our results indicate that changes in precipitation cannot by themselves be the sole cause of substantial D2M variability in drought over most parts of North America.

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REFERENCES


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