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ARTICLE

Long-Term Hydrologic Variability in the Instrumental Record of California Climate

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ABSTRACT

This study characterizes the instrumental record of California climate for the last 170 years. Our goal is to look for hydrologic variability at decadal and longer time scales that would be consistent with paleoclimate estimates of hydrologic variability in California for the last 3000 years. Our study focuses on meteorological summaries of annual precipitation and temperature. The precipitation records go back as far as 1850; the temperature records go back as far as 1880. California hydrologic records show strong variability at the interannual level due to ENSO forcing. They also all show a strong decadal (∼14 yr) cyclicity and evidence for multi-decadal to centennial variability that is consistent with California paleoclimate studies. California temperature records show a long-term warming of 5 °F−6 °F (2.8 °C−3.4 °C) associated with global warming, but there is no evidence for a similar long-term trend in hydrologic variability. Long-term Pacific Ocean variability adjacent to central and northern California, Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO), show a similar decadal to centennial pattern of variability that we associate with our long-term hydrologic variability. The positive phase of the NPGO and the negative phase of the PDO are associated with the decadal scale (∼14 yr) dry cycles in California for the last 70 years.

Keywords: California Climate; California Hydrologic Variability; California Rainfall; California Temperature; Global Warming

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1. Introduction

We have recently summarized the paleoclimate record of hydrologic variability in California for the last ∼3000 years[1–3]. The hydrologic estimates have come from lake sediment studies (**Figure 1**, black large circles) using three proxies (magnetic susceptibility, total inorganic carbon (TIC), and $\delta^{18}O$) to reconstruct lake level and presumable precipitation influx (rainfall or snowpack melt). We have also compared these records with tree-ring thickness estimates of hydrological variability (**Figure 1**, grey large circles). The two different data types are consistent with one another at the decadal and longer-term scale. These studies have shown that there is significant paleohydrologic variability across California at the decadal to millennial scale. Our paleoclimate records extend to the present, in most cases, but human activity has complicated the youngest part of the lake sediment paleoclimate records. This study looks for long-term (decadal to centennial) evidence for hydrologic variability in the instrumental record of California climate over the last ∼170 years. We hope to find some overlapping pattern of historic hydrologic variability that can better document what perhaps caused the paleoclimate record of California hydrologic variability.

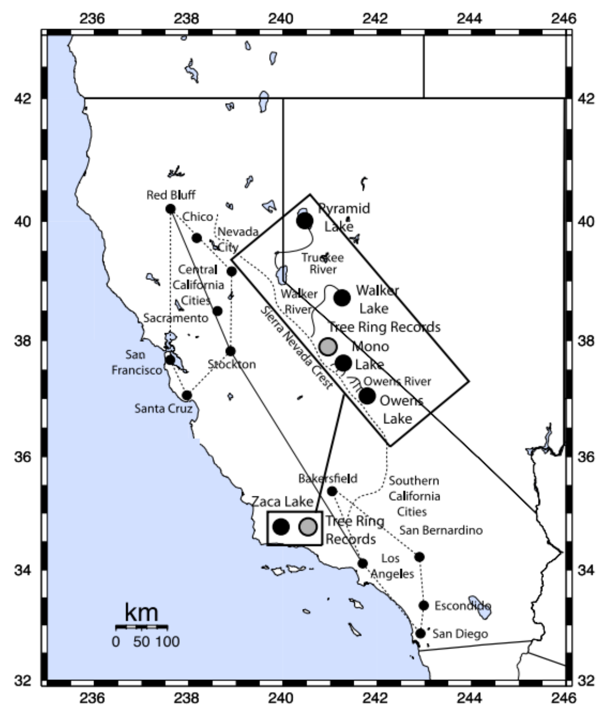

Figure 1. Map of California showing key paleoclimatic records and instrumental records of climate variability.

This study focuses on meteorologic summaries of annual precipitation and temperature across central and southern California, the regions studied in our paleoclimate studies (**Figure 1**, small dots). The precipitation records go back as far as 1850; the temperature records go back as far as 1880. We also compare selected regional indices for long-term (decadal and longer) variability in the Pacific Ocean (the Pacific-Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO)) that occur adjacent to the California region and may influence California hydrologic variability.

2. Hydrologic Variability

Instrumental records of annual precipitation (rainfall/snowfall) are documented at the Western Climate Data Center (Desert Research Institute in coordination with NOAA, http://www.wrcc.dri.edu). We have selected two grids of instrumental records from central California and southern California (**Figure 1, dashed regions**). The central California grid focuses on seven of the longest recording sites in the central to northern San Joaquin Valley bounded by the Sierra Nevada Mountains on the east. The Southern California grid focuses on five of the longest recording sites in southern California bounded by the Peninsular Ranges on the east.

Figures 2 and **3** (Santa Cruz only) display the annual (small dots) and 5-yr average (large dots) precipitation for central California sites from 1850 to 2020. **Figure 3** displays the annual and 5-yr average precipitation for southern California s from 1850 to 2020. The five-year smoothing largely removes the interannual variability associated with El-Nino/Southern Oscillation (ENSO) that has primary spectral power at ∼2.5−5 years[4]. The solid horizontal lines indicate the long-term average precipitation at each site; the dashed lines indicate the level of the most recent multi-year drought interval at each site. There is also a least-squares solid trend line in each record to assess long-term changes in annual precipitation.

All of our sites display significant decadal-scale precipitation variability. Letters A'−L (**Figures 2** and **3**) indicate decadal wet intervals that are synchronous across central to southern California. The most recent decadal scale drought interval is no drier than several other decadal drought intervals of the last 170 years. There is no evidence for consistent long-term (centennial-scale) precipitation changes within either central or southern California.

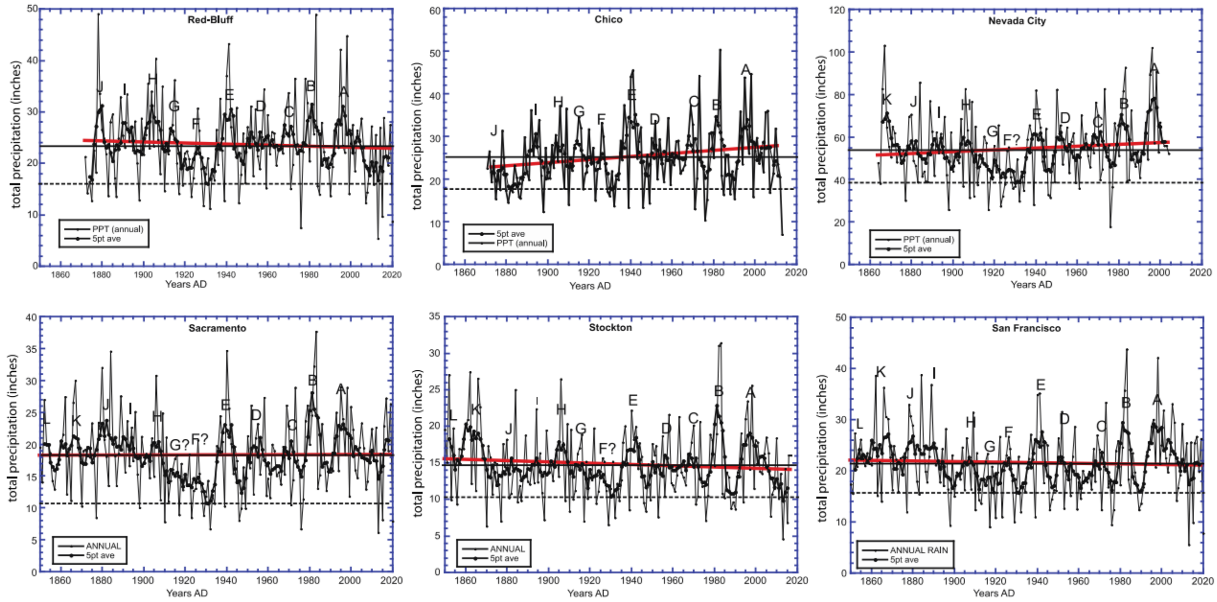

Figure 2. Annual records of hydrologic variability at six Central California sites H.

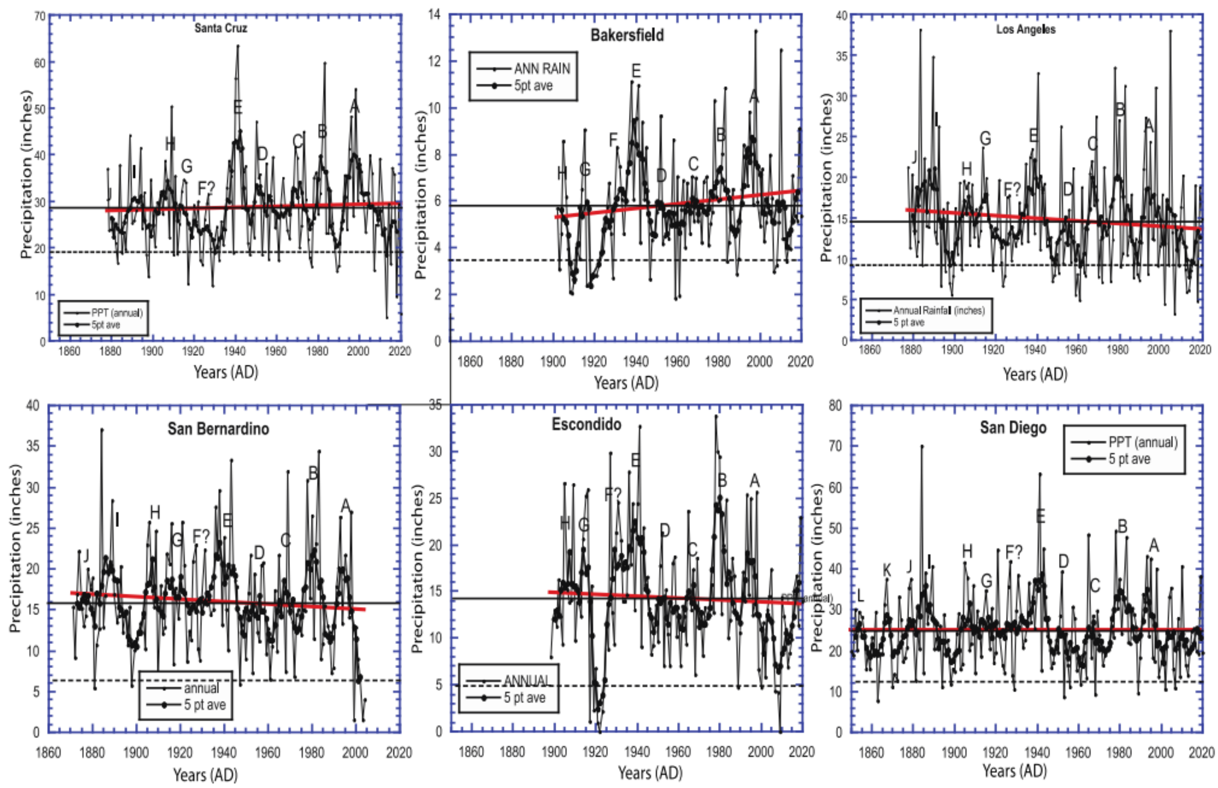

Figure 3. Annual records of hydrologic variability at one Central California site and five Southern California sites.

Figure 4 shows the 5-yr average precipitation for the central California region. This smoothing minimizes the ENSO scale inter-annual hydrologic variability[4] and focuses on decadal and longer-term hydrologic variations. The decadal wet intervals A−K (**Table 1**), shown in **Figures 2** and **3**, and dry intervals 1−13 (**Table 1**) are labeled here. Vertical dashed lines indicate the centers of synchronous intervening decadal dry intervals over the last 170 years (**Table 1**). The time intervals between drought intervals are noted at top. There is a clear ∼14 yr cyclicity in drought (and wet) intervals. This decadal cyclicity has dominated precipitation variability for the entire interval of instrumental records. Specific notable dry years (open circles), wet years (solid circles), and El-Ninos (arrows) are also noted at the top of **Figure 4**. It is interesting to note that the notable wet years and El-Ninos all occur within the individual decadal-scale wet intervals (A−L). A previous study of California hydrologic variability did not document this decadal cyclicity [5].

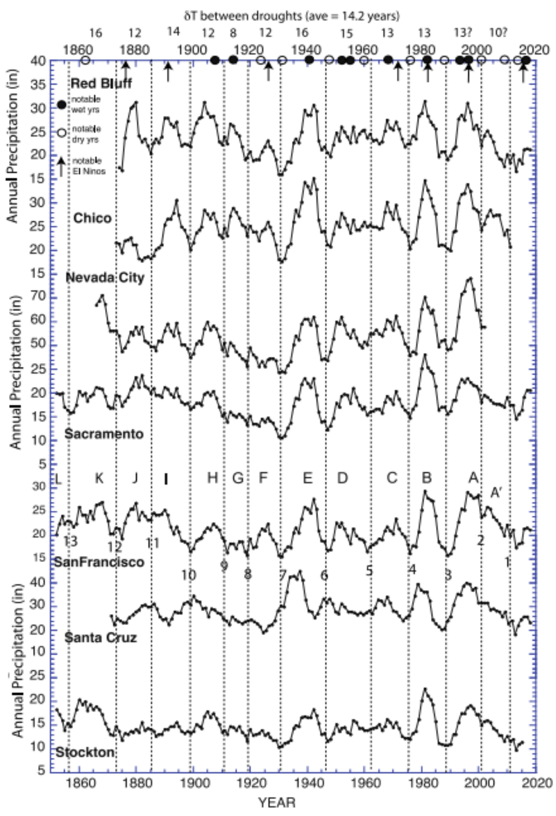

Figure 4. Five-year average hydrologic records for Central California.

All of these indications of hydrological variability are synchronous from Red Bluff in north-central California to San Diego and from coastal Los Angeles, Santa Cruz, and San Francisco to the edge of the eastern Peninsular Ranges and Sierra Nevada. They all show evidence for decadal (∼14 yr) cyclicity in precipitation, beyond the well-known ENSO scale of interannual hydrologic variability.

3. Temperature Variability

Figure 5 shows the temperature and precipitation variability for four of the longest-duration sites that span north-central to southern California (**Figure 1**). The temperature variability is quite different in style from that of the associated precipitation. The temperature has typically less than 2 °F variability in successive years, but all of these individual records display a significant trend to warmer temperatures since the mid 20th century **Figure 5**, dashed lines). All four of the records in **Figure 5** show a 5 °F to 6 °F increase in annual temperature to present day. That translates to a 2.8 °C to 3.3 °C temperature rise that should be associated with current global warming. This warming is greater than noted in stacked California-wide averages in older studies [5, 6]. This is significantly higher than the global average increased temperature associated with global warming (∼1 °C).

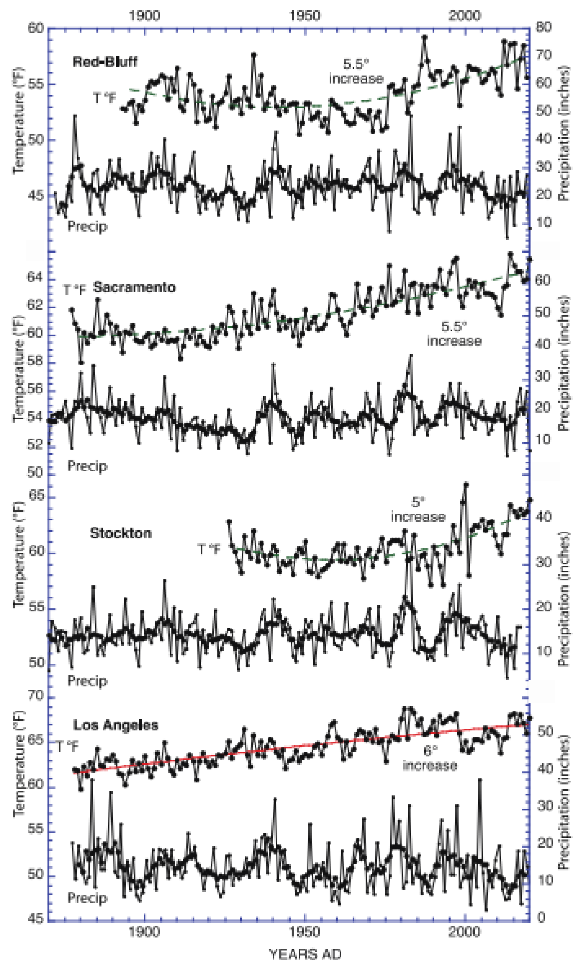

Figure 5. Temperature and hydrologic annual records for four California sites.

The associated precipitation records in **Figure 5** show no significant evidence for a change in hydrologic variability as California temperatures have increased by 5 °F−6 °F. An ongoing question is how precipitation patterns will change in the future as global warming continues. So far precipitation patterns have not changed even though temperatures have increased significantly.

4. Spectral Analysis of Hydrologic Variability

We use spectral analysis of the scalar time series presented above to quantify the frequency content of the California hydrological variability. All time series analysed are annual records. The scalar records were analysed using both a fast Fourier transform (FFT) or periodogram method and a maximum entropy method (MEM)[7]. Scalar spectral analysis used the program Analyseries 2.0.8[8]. The program was used to calculate a periodogram and several MEM estimates (both after removal of any linear trend). Several MEM spectra were generated with varying prediction error filters[9, 10], from 10% to 40% of each time series length. Stable MEM spectral estimates were generated with filter lengths of 15% to 30%.

Typical spectra for three rainfall records—Nevada City, Santa Cruz, Los Angeles—are shown in **Figure 6**. The top spectrum for each city is the periodogram spectrum; the bottom spectrum is the MEM spectrum with three different prediction error filters. In all cases, the periodogram and MEM spectra give comparable spectral peaks. Each record shows a group of three spectral peaks at the interannual interval (~5.2 years, 3.2 years, and 2.4 years). These periods are associated with ENSO variability[4, 11, 12]. The records also show two strong spectral peaks at the decadal to centennial interval (~13 years and either~40 years or ~100 years). **Figure 7** summarizes the spectral peaks for all the hydrologic records. It is worth noting that all Central and Southern California sites show a 39 ± 5 year multidecadal spectral peak, a 13.5 ± 2 year decadal spectral peak and a sequence of three interannual spectral peaks (5.2 ± 1 years, 3.1 ± 0.5 years, and 2.4 ± 0.2 years). The durations of the time series for each city are listed at left. The longest duration time series in Central California also show evidence of a 91 ± 10 year multi-decadal/centennial spectral peak. Previous spectral analyses of California rainfall have focused on the interannual variability[4, 11, 12], but none of them have noted the decadal to centennial-scale spectral peaks.

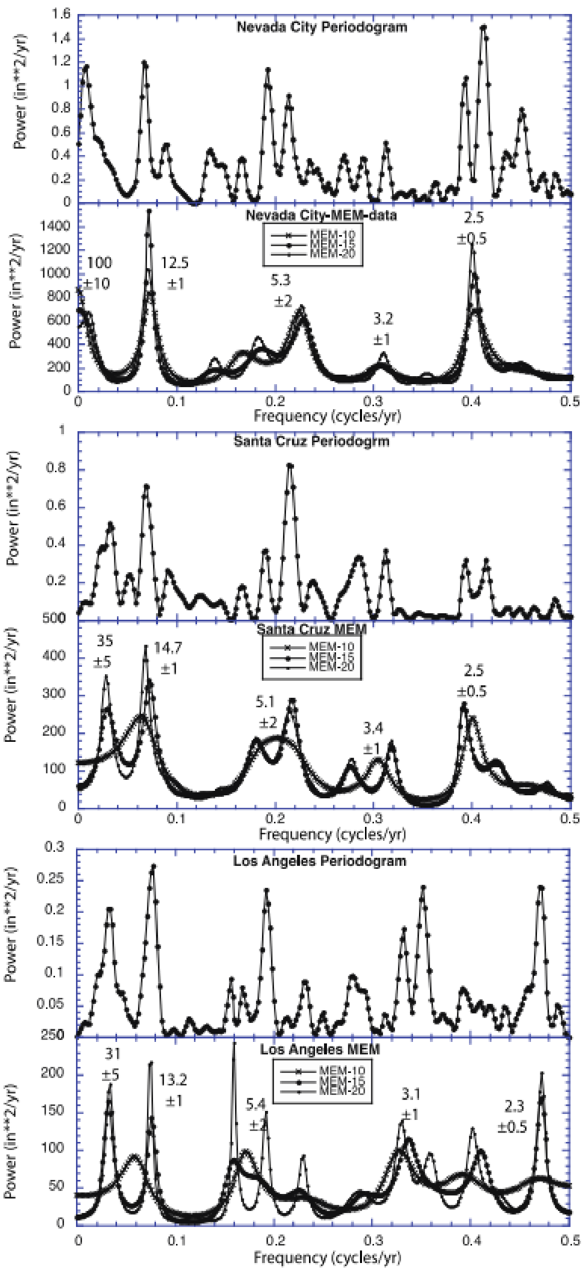

Figure 6. Spectral analysis of three selected California hydrologic records.

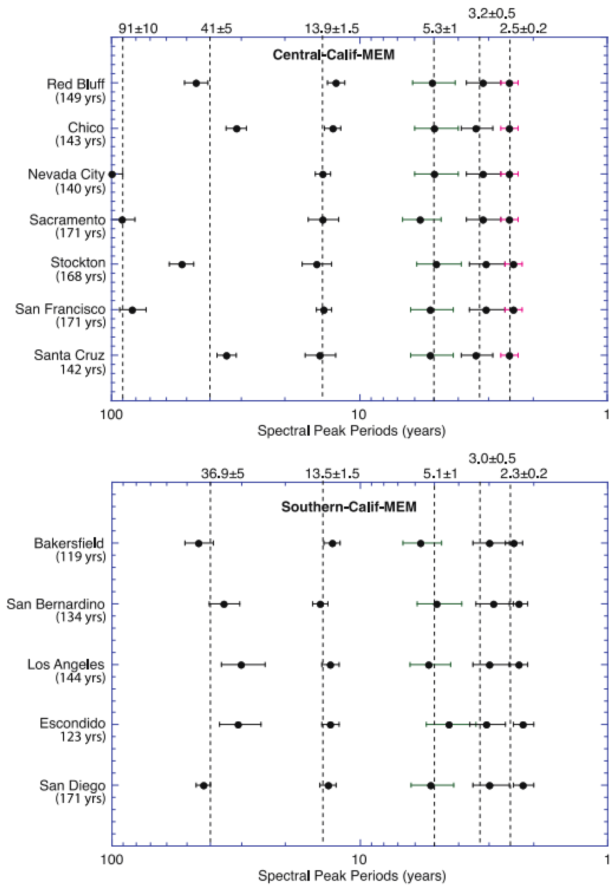

Figure 7. Summary of notable spectral peaks for all of the California hydrologic records.

5. Adjacent Long-Term Pacific Ocean Variability

North Pacific Ocean variability adjacent to California on instrumental time scales is usually described in terms of three indices, ENSO variability, Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO). ENSO, as noted above, is primarily an interannual pattern of variability that affects California hydrologic records[4]. PDO and NPGO are primarily decadal to longer-term patterns of variability. The PDO describes the spatial and temporal variability in sea surface temperature (SST) and sea level pressure (SLP) in the North Pacific Ocean[13, 14]. The index primarily notes the contrast in SSTs in the North Pacific Ocean relative to SSTs along the California margin. The 'Warm Phase' of the PDO has warmer SSTs along the California margin and the 'Cold Phase' has colder SSTs along the California margin. There is a strong ∼50−70 year cyclicity in the PDO that is known to relate to long-term fisheries variability in the Pacific Ocean[13, 14]. There is also evidence for a ∼15−25 year cyclicity in the PDO record[14, 15].

Several studies[16–18] have identified a largely synchronous decadal to multi-decadal pattern to salinity and nutrient variations in the California Current off the western USA coast and Gulf of Alaska. The NPGO is an index that is determined from analysis of sea surface height (SSHa) and sea surface temperatures (SSTa) in the NE Pacific over the region 180° W−110° W, 25° N−62° N. This pattern of variability also explains a variety of fluctuations in Pacific fish populations. The PDO is a first EOF/PC of both the SSHa and SSTa in this region. The NPGO represents the second EOF/PC in this region[17]. Practically, the positive phase of the NPGO is associated with increased intensity of the eastern North Pacific gyre circulation with increased upwelling and horizontal advection. The increased North Pacific gyre circulation (positive phase of the NPGO) has colder California Current SSTs (negative phase of the PDO).

Spectral analysis of the PDO, and NPGO time series are shown in **Figure 8**. They are all dominated by decadal to multi-decadal spectral peaks. Both show evidence of ∼12-year and 25−35 year spectral peaks that are present in the California hydrologic records. These spectra are consistent with previous estimates of PDO and NPGO variability[13–18]. None of the records show any evidence of longer-term (centennial-scale) peaks. What is most interesting is that the NPGO is strongly dominated by a ∼12-year spectral peak that is comparable to the 13.5 ± 2 spectral peak (decadal wet/dry cycles) present in all California hydrologic records. This aspect of the NPGO has been previously noted[19].

Figure 9 shows the PDO and NPGO indices for the last 70 years. The centers of our previously noted multiyear droughts (∼14 yr cyclicity) in California (**Figure 4**) (**Table 1**) are shown by vertical dashed lines; the wet (A'−D) and dry (1−5) intervals are labeled as well. It is clear that droughts are associated with colder California Current SSTs, the negative phase if the PDO, and the positive phase of the NPGO.

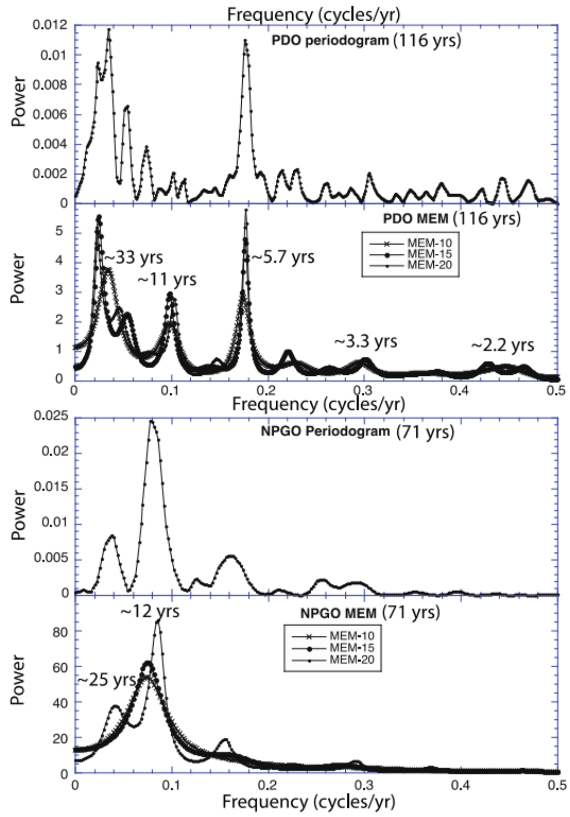

Figure 8. Spectral analysis of PDO and NPGO time series.

Table 1. Decadal cycles in hydrologic variability.

Wet Interval	Dry Interval	Center Age
	1	2011
A'		2005
	2	2001
A		1995
	3	1988
B		1981
	4	1975
C		1968
	5	1962
D		1954
	9	1946
E		1941
	7	1931
F		1926
	8	1919
G		1915
	9	1911
H		1906
	10	1899
I		1890
	11	1885
J		1880
	12	1873
K		1868
	13	1857
L		1852

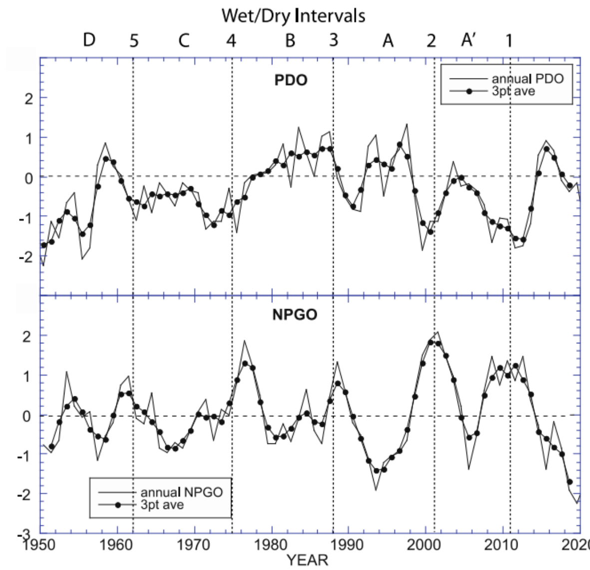

Figure 9. Plot of PDO, and NPGO. Vertical dashed lines are California 14-yr hydrologic dry intervals.

6. Discussion

Spectral analysis of the California hydrologic records shows that precipitation, west of the Sierra Nevada and Peninsular Ranges, is coherent in its amplitude and frequency variability. All of the records from Red Bluff in the north to San Diego in the south have a consistent pattern of variability due to interannual variability (~5.2 years, ~3.1 years, and ~2.4 years) of ENSO forcing.

All of the records also show a consistent pattern of variability at the decadal to centennial scale that we think relates to our paleoclimate hydrologic variability of the last 3,000 years. The most distinctive element of that longer-term California hydrologic variability is a 13.5 ± 1.5 year cyclicity over the last 170 years that we broadly associate with the historic oscillating drought cycle—~5−10 years of drought followed by 5−10 years of wet conditions (**Figure 4**). What is unexpected is that the NPGO variability largely records the same pattern of variability with a dominant spectral peak at ~14 years[19]. The positive phase of the NPGO is associated with hydrologic drought conditions across California. The negative phase of the PDO is also associated with the hydrologic drought conditions.

There is also a persistent longer-term ~35 yr cycle in hydrologic variability in both Central and Southern California that is consistent with PDO variability (**Figure 8**). Others have commented on this multi-decadal influence of PDO on climate variability [14, 20].

The longest spectral peaks (∼100 years) in the central California hydrologic records (but not Southern California) do show evidence of a centennial-scale hydrologic variability. This region (Central California) is also the region where most of our paleoclimate records come from (**Figure 1**). PDO and NPGO dominate central to northerly Pacific climate variability. Their decadal and longer-term variability are most likely to cause our multi-decadal to centennial-scale central California hydrologic variability. Our southern California hydrologic records may be more influenced by equatorial ENSO interannual hydrologic variability so that they do not record the longer-duration central California centennial-scale hydrologic variability.

7. Conclusions

This study characterizes the instrumental record of California climate for the last 170 years. One goal is to look for hydrologic variability at decadal and longer scales that would be consistent with our paleoclimate estimates of hydrologic variability for the last 3000 years. Our study focuses on meteorological summaries of annual precipitation and temperature throughout California. The precipitation records go back as far as 1850; the temperature records go back as far as 1880.

California hydrologic records show strong variability at the interannual level due to ENSO forcing. They also all show a strong decadal (∼14 yr) cyclicity that we associate with historic multi-year droughts. This decadal pattern has not been clearly documented before. California temperature records show a long-term warming of 5 °F–6 °F (2.8 °C–3.4 °C). However, the hydrologic records show no evidence of a similar long-term trend.

All the California hydrologic records show evidence of a multi-decadal (∼35 yr) cyclicity. The central California (but not Southern California) hydrologic records also show evidence of a centennial-scale variability that is consistent with our paleoclimate studies.

The long-term oceanographic indices (PDO, NPGO) show strong decadal to multi-decadal variability with similar spectra to our long-term California hydrologic records. The positive phase of the NPGO and the negative phase of the PDO appear to be associated with the decadal-scale (∼14 yr) wet/dry cycle in California.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All of the basic data used in this study are publically available online.

Conflicts of Interest

The author has no conflict of interest in this manuscript. He has received no payment for this manuscript and has no personal relationship with anyone associated with the 30th PACLIM Proceedings.

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