Relationships Between Climate Variability and Fluctuations in Daily Precipitation over the United States

by

R. W. Higgins[1], V. B. S. Silva[2], W. Shi[1] and J. Larson[2]

[1]Climate Prediction Center, NOAA/NWS/NCEP, Camp Springs, MD
[2]RS Information Systems, Mclean, VA

October 2006

(Submitted to *Journal of Climate*)

Corresponding author address: Dr. R. W. Higgins, Development Branch,
Climate Prediction Center, NOAA/NWS/NCEP,
Washington, DC, 20233, USA

Abstract

Fluctuations in the frequency of daily precipitation occurrence and in the intensity of daily precipitation over the United States during the period 1948-2004 are identified and linked to leading sources of interannual and interdecadal climate variability. The El Niño-Southern Oscillation (ENSO) phenomena are implicated in interannual fluctuations while the Pacific Decadal Oscillation (PDO) and the Arctic Oscillation (AO) are linked to recent interdecadal fluctuations.

For the conterminous United States as a whole there have been increases in the annual frequency of occurrence of wet days and heavy precipitation days and in the mean daily and annual total precipitation over the past several decades, though these changes have not been uniform. The possibility of significant natural forcing of these interdecadal variations in precipitation is explored. It is shown that the PDO is associated with these fluctuations over the western and southern United States, while the AO is also associated with them but to a much lesser extent over the southeastern United States. Because the interdecadal fluctuations are linked to changes in the global scale circulation and sea surface temperatures associated with the PDO, the results imply that a significant portion of the skill of climate models in anticipating fluctuations in daily precipitation statistics over the United States will arise from an ability to forecast the temporal and spatial variability of the interdecadal shifts in tropical precipitation and in the associated teleconnection patterns into midlatitudes.

1. Introduction

Progress in determining how natural climate variability and change are related to extreme precipitation events has been hampered by a lack of accurate and complete long term estimates of precipitation at high spatial and temporal resolution. There are many problems with the climate records for precipitation (e.g. Easterling et al. 2000), including inaccessibility of sufficiently long data records at daily timescales, incomplete and declining spatial coverage, and lack of consistent, high resolution, quality controlled analyses. Several previous studies have been successful in identifying the basic characteristics of trends in extreme precipitation events over the past several decades for specific regions such as the United States (e.g. Karl et al. 1995; Karl and Knight 1998, Changnon 1998, Kunkel et al. 1999, Easterling et al. 2000, Groisman et al. (1998, 2001, 2004, 2005)), but additional studies of the mechanisms that relate climate variability and change to the frequency of occurrence of daily precipitation events are needed.

Most areas of the globe are not adequately sampled, either by in situ or remote sensing, which makes accurate quantification of the basic statistical aspects of daily precipitation difficult to document. However, over the past decade the Climate Prediction Center (CPC) has developed a Unified Raingauge Database (URD) consisting of daily data from multiple sources and a precipitation quality control system and analysis (Higgins et al. 2000b) that permits reasonable quantitative estimates of daily precipitation statistics over the United States. An important aspect of the present study is to demonstrate this capability by exploiting a historical (1948-2004) daily precipitation analysis for the United States to address the following basic question:

> *What are the observed characteristics of fluctuations in daily precipitation occurrence and extremes over the United States, and how are they changing?*

Evidence is mounting that some primary patterns of climate variability can significantly alter the daily weather patterns including the frequencies, intensities and locations of extreme events (e.g. floods, droughts, hurricanes). These patterns include ENSO (e.g. Gershunov and Barnett 1998a; Gershunov 1998; Cayan et al. 1999; Gershunov and Cayan 2003; US CCSP 2003), ENSO-like decadal variability (e.g. Gershunov and Barnett 1998b; Gershunov et al. 1999), the Northern Hemisphere and Southern Hemisphere annular modes (Thompson and Wallace 1998; Thompson and Wallace 2001) and possibly others. In addition, Groisman et al. (1998, 2001, 2004, 2005) have documented the existence of long-term trends in heavy precipitation events in the U.S. that are likely to provide a significant source of seasonal predictability, especially in non-ENSO years.

Fortunately, over the past decade it has been recognized that much of climate variability is associated with a relatively small number of these recurrent patterns or modes (e.g. Higgins et al. 2000a). This makes it possible to investigate relationships between these modes and fluctuations in the characteristics of the daily weather patterns.

The El Niño / Southern Oscillation (ENSO) phenomenon is the major, and best understood, source of interannual climate variability. For most of the world, El Niño is considered to be an abnormal warming of the equatorial Pacific that has a recognizable signature in the global patterns of atmospheric pressure (e.g. Walker and Bliss 1932, Troup 1965, Berlage 1966; Bjerknes 1966, 1969), atmospheric circulation (e.g. Arkin 1982), and precipitation and temperature patterns (e.g. Caviedes 1973; Hastenrath and Heller 1977; Rasmusson and Carpenter 1983; Bhlame et al. 1983; Kousky et al. 1984; Ropelewski and Halpert 1986, 1987; Aceituno 1988; Kiladis and Diaz 1989; Halpert and

Ropelewski 1992). Over the past couple of decades, the concept of the ENSO cycle has developed (e.g. Horel and Wallace 1981; Simmons et al. 1983; Held and Kang 1987; Karoly et al. 1989; Rasmusson and Mo 1993), which includes a warm phase (El Niño) at intervals of every 4-5 years, a cold phase (La Niña), and intervening transition periods characterized by near-normal ocean temperatures.

Conventional ENSO indices based on equatorial Pacific sea surface temperature or the sea-level pressure difference between Darwin and Tahiti exhibit very little variability from one decade to the next. However, many of the tropical and extratropical expressions of ENSO exhibited a long term shift toward more 'El Niño-like' conditions after 1975 (e.g. Nita and Yamada 1989; Trenberth 1990; Trenberth and Hurrell 1994; Graham 1994; Latif and Barnett 1994, Gu and Philander 1997), which was detectable in a variety of Pacific basin ecological systems (e.g. Ebbesmeyer et al. 1991; Mantua et al. 1997). There is well documented evidence of an analogous climate shift, but in the opposite sense around 1946 (and possibly also after the mid-1990's), that has also had a discernable influence on wintertime temperature and rainfall patterns over the United States (Zhang et al. 1997; Mantua et al. 1997; Hare and Mantua 2000; Dettinger et al. 1998; Higgins et al. 2000a). This longer term Pacific decadal variability is often referred to as the Pacific Decadal Oscillation (PDO) (e.g. Mantua et al. 1997) and we will use that notation here. Gershunov and Barnett (1998) have argued that the effect of the PDO on precipitation (specifically the frequency of extreme daily rainfall) over the contiguous U.S. is largely through its modulation of ENSO.

The circulations of both hemispheres exhibit important ring-like (or annular) modes of variability encircling the poles that fluctuate on time scales ranging from a week to decades (e.g. Thompson and Wallace 2000). The Northern Hemisphere annular mode, often referred to as the Arctic Oscillation (AO) (Thompson and Wallace 1998), is marked by opposing fluctuations in barometric pressure over the polar cap region and the midlatitudes, together with opposing fluctuations in the strength of the westerlies at subpolar and subtropical latitudes. The AO has wide ranging effects on weather over North America, Europe and Asia (e.g. Thompson and Wallace 1998; Thompson and Wallace 2001). During the period from 1960-1990 a trend towards lower pressure over the poles, higher pressure in midlatitudes and stronger subpolar westerlies indicated a more persistent positive phase of the AO (Thompson et al. 2000). Since 1990 a discernable trend in the AO is less clear. The well-known North Atlantic Oscillation (NAO) teleconnection pattern (Hurrell 1995) can be viewed as the regional expression of the AO in the Atlantic sector (Wallace 2000), though questions remain on the dominance of the AO versus the NAO (e.g. Ambaum et al. 2001). There is also evidence for tropical forcing of recent NAO activity (e.g. Hoerling et al. 2001). A substantial portion of the AO variability is chaotic, or random (e.g. Frederiksen and Zheng 2004), so it remains to be determined what fraction of the AO variability is potentially predictable at seasonal-to-interannual timescales.

Focused study of these leading sources of climate variability over the last several years has revealed that they account for much of the systematic (i.e. predictable) portion of the atmospheric variability on seasonal-to-interannual-to-decadal timescales (e.g. Higgins et al. 2000a). The background variability that remains after the effects of these leading modes are accounted for and removed from the climate record (referred to as a residual) is attributable to other possible factors including (1) random chance, (2) poorly understood episodic phenomena (including other forms of natural climate variability, possible interactions of the effects of the main climate modes), (3) changes in the observing system, (4) global warming, and (5) anthropogenic influences. Statistical relationships between temporal indices of the leading sources of climate variability and changes in daily weather patterns (both temperature and precipitation) can provide quite detailed information on the climatic signature of these modes. Motivated by this, we employ the historical daily precipitation analysis for the United States discussed above and appropriate indices for ENSO, the PDO and the AO to examine some aspects of a second key question:

> *What are the relationships between these leading sources of climate variability and fluctuations in the frequency of daily precipitation occurrence over the United States on interannual and interdecadal time scales?*

The current study is an extension of our earlier work (Higgins et al. 2000a), which emphasized the influence of the leading sources of climate variability on the seasonal predictability and long term trends of U.S. precipitation. It builds on the results of previous studies (cited above) that have considered the interpretation of the leading modes of climate variability, and their possible role in the variability and predictability of precipitation. Here we focus on daily statistics and highlight changes that have occurred between the periods before and after the mid-1970s. Geographic maps are used to examine these fluctuations in more detail for all wet days and for specific thresholds (e.g. 90th percentile events). Because the analyses are carried out at higher spatial and temporal resolution than in our previous work, the results are in a form convenient for validation of state-of-the-art model simulations, such as the high-resolution simulations with the NOAA coupled Climate Forecast System currently underway at the National Centers for Environmental Prediction (NCEP). We note that the present study does not emphasize precipitation events with durations longer than a day, though we recognize the need for improved understanding of relationships between multi-day rain events and flooding.

The datasets and analysis procedures used in this study are discussed in section 2. A brief review of the climatology of precipitation for the conterminous United States based on the URD is given in section 3 prior to the detailed analysis of daily precipitation statistics which are examined in detail in section 4. NOAA operational definitions for El Niño and La Niña are used to relate ENSO to daily precipitation statistics in section 5. Changes in the frequency of daily precipitation between the periods (1948-1975) and (1976-2004), chosen to separate the well documented climate shift towards more El-Niño like conditions after 1975, are discussed in section 6. Linear regression techniques are used in section 7 to determine relationships between the PDO, the AO, and observed changes in the frequency of daily precipitation occurrence over the past few decades. A summary and future plans are given in section 8.

2. Data sets and analysis procedures

The daily precipitation analysis is obtained from CPC's Unified Raingauge Database (Higgins et al. 2000b). The database contains information from over 8000 stations across the United States each day. Typically, the station density is highest in the eastern two-thirds of the United States, but coverage over the western United States is relatively good; geographic distributions of station data and the associated daily analysis are shown on the CPC website (www.cpc.ncep.noaa.gov/products/precip/realtime/us_precip.shtml). The

URD was used to produce the multi-year (1948-2004) daily precipitation analysis (12Z-12Z) for the United States. The daily data were gridded at a horizontal resolution of (lat, lon)=(0.25°x0.25°) over the domain (140^{o}W-60^{o}W,10^{o}N-60^{o}N) using a Cressman (1959) scheme with modifications (Glahn et al. 1985; Charba et al. 1992). Several types of QC were applied including a "duplicate station check" to eliminate duplicates and key punch errors, a "buddy check" to eliminate erroneous extreme values, and a standard deviation check that compares the daily raingauge data against a gridded daily climatology (see Higgins et al. 2000b for details).

A classification of historical warm (El Niño) and cold (La Niña) episodes developed by NOAA's Climate Prediction Center is used to examine relationships between ENSO and fluctuations in daily precipitation statistics. The historical episodes are identified using an Oceanic Niño Index (ONI), which is one of the principal measures used by NOAA for monitoring and assessing ENSO. The ONI is computed from three-month running-mean values of SST departures from average in the Niño 3.4 region using a set of improved homogeneous historical SST analyses (Extended Reconstructed SST – ERSST.v2 of Smith and Reynolds 2003). The NOAA operational definitions of El Niño and La Niña are keyed to the ONI: (i) **El Niño:** characterized by a *positive* ONI greater than or equal to +0.5°C; (ii) **La Niña:** characterized by a *negative* ONI less than or equal to -0.5°C. These definitions properly identify all historical warm and cold episodes (defined as 5 consecutive 3-month seasons in which the El Niño or La Niña definition is satisfied) back to 1950. Numerical values of the ONI for each 3-month season since 1950 and Tables of historical warm and cold episodes are found on the CPC website at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml

The PDO index is derived as the leading PC of low pass filtered monthly SST anomalies in the Pacific Ocean north of 20° N (Mantua et al. 1997; Zhang et al. 1997). The monthly mean global average SST anomalies for the period of record have been removed to separate this pattern of variability from any "global warming" signal that may be present in the data. The AO index was developed at CPC for real-time monitoring purposes by applying the methodology of Thompson and Wallace 1998. The AO index is defined on the basis of the leading principal component time series of monthly-mean NH 1000-hPa height anomalies for all months of the year. Anomalies are with respect to 1979-2000 base period monthly means. Details are found on the CPC web page at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml

Annual time series of the ONI, PDO and AO indices (1948-2004) are shown in Fig. 1. Each index has been normalized by the annual standard deviation in the index. Trends in the PDO and AO indices are clearly evident.

In section 7 linear regression techniques are used to examine relationships between the PDO, the AO and observed changes in the frequency of daily precipitation occurrence over the United States. The calculations are based on differences between the period (1976-2004) and (1948-1975) computed from the observed data at each gridpoint. Relationships between the climate variability and changes in precipitation statistics are estimated quantitatively as follows: (i) regress the observed precipitation time series onto the PDO (or AO) index to obtain regression coefficients, (ii) reconstruct the time series using the regression coefficients and the appropriate index, and (iii) take the difference between the period (1976-2004) and (1948-1975) using the reconstructed time series. These computations provide quantitative estimates of the influence of the PDO and AO to the observed fluctuations between the two periods. A residual is computed by removing the PDO and AO estimates from the total observed change between the two periods; the residual includes several possible components as discussed in section 1. We note that this methodology has been applied in our earlier studies (e.g. Higgins et al. 2000a) to examine the dominant factors influencing trends in seasonal mean United States precipitation and surface air temperature, but it has not been used to examine changes in the frequency of daily precipitation occurrence.

Critical values of the change in frequency of daily precipitation occurrence, of the change in total precipitation accumulation, and of the composite mean differences in the ENSO composites were evaluated statistically using a *t* test. The effective time between independent samples was computed using the method of Livezey (1995). In each case statistical significance was assessed relative to the 95% confidence level.

3. Climatology

A brief review of the climatology of precipitation for the conterminous United States based on the URD is given so that fluctuations in the daily precipitation statistics can be characterized in a proper historical context.

The mean (1948-2004) annual precipitation based on the daily precipitation analysis for the United States is shown in Fig. 2. In an annual mean sense the wettest parts of the continent are in the Pacific Northwest and along the Gulf Coast, where annual average precipitation amounts exceed 1500 mm (60 in) at some locations. The driest areas of the continent are in the Desert Southwest where annual precipitation below 250 mm (10 in) is common. In portions of the West the data in the URD is more limited, and the terrain is very complex, which may contribute to significant errors in the analysis in these regions.

A Pacific Northwest precipitation maximum occurs in the fall and winter, but it is nearly absent in summer. A central Gulf Coast precipitation maximum occurs throughout the annual cycle, but it is suppressed to the immediate Gulf Coast and includes Florida during the summer months. During the summer a precipitation maximum occurs over the Great Plains in association with increased nocturnal convection.

4. Daily Statistics

4.1 Frequency

The pattern of mean (1948-2004) annual frequency of measurable (> 1 mm) daily precipitation occurrence in the United States (Fig. 3a) is similar in many respects to the pattern of mean annual precipitation (Fig. 2). The highest frequencies (greater than 40% of the days) tend to occur in the same regions as the largest annual precipitation totals. One exception is along the western slopes of the Appalachians, where the frequency of measurable daily precipitation is relatively high but the annual precipitation totals are not as high as in the Pacific Northwest and along the Gulf Coast. The lowest frequencies (less than 10% of the days) occur in the Desert Southwest where the mean annual precipitation is small.

Because the data have been objectively analyzed, the spatial coverage of light events is somewhat high and the coverage of heavy rainfall events is somewhat low. These are artifacts of all objective analysis techniques including the Cressman scheme. To explore the sensitivity of the frequency of measurable daily precipitation occurrence to the precipitation threshold, we show results for a threshold > 25 mm (Fig. 3b). At this threshold the highest frequencies (3-4% of the days) are found in the regions mentioned above.

Daily precipitation statistics from the gridded analysis and the station observations for several major cities in the United States are compared in Table 1. At a threshold of 1 mm the station observations yield mean annual frequencies of daily precipitation occurrence that are up to a factor of two lower than the analyzed frequencies at the more arid locations (e.g. Dallas, Los Angeles and Phoenix). A comparison of the frequency of extreme events (>25 mm) shows that there are generally fewer of them in the gridded analysis than at the stations, except at the west coast sites (Seattle and Los Angeles). Annual precipitation totals tend to be comparable or lower at individual stations compared to the corresponding gridpoints, except at the wettest coastal locations (e.g. Seattle and Miami) where individual daily events tend to be heavier and influenced to a lesser extent by surrounding observations in the objective analysis. The standard deviation of daily precipitation is somewhat higher at the station locations than at the corresponding gridpoints. Though the results indicate that daily precipitation frequencies at a threshold of 1 mm (25 mm) may be generally too high (too low) in the gridded analysis, this will not change the interpretation of the results in the remainder of this paper.

There is a large seasonal cycle in the frequency of daily precipitation occurrence in the Pacific Northwest (frequencies exceed 50% of the days during the winter, but drop to less than 30% of the days during the summer) and in the monsoon regions of the Southwest (not shown). In contrast, the seasonal cycle is relatively small over the eastern two-thirds of the United States.

An examination of the mean frequency of measurable (> 1 mm) daily precipitation occurrence by decade (1950s, 1960s, 1980s, 1980s and 1990s), expressed as a percent departure from the frequency for the entire period (1948-2004) (Fig. 4) shows that daily precipitation events have increased over much of the western half of the United States (more than 30% at some locations) over the five decade period. Some of the signal in the west (particularly at high elevations) may be due to overestimates of the frequency of occurrence of light intensity events by the objective analysis scheme combined with fluctuations in the station coverage (see section 5).

The standard deviation of the frequency of measurable (> 1 mm) daily precipitation occurrence shows a very different pattern for the NH summer (JAS) as compared to the other seasons. During autumn, winter and spring, the highest values are found in the Pacific Northwest and along the central Gulf Coast due to synoptic-scale storm systems and mid-latitude fronts that provide focusing mechanisms for precipitation episodes. In summer the variability in these regions is much lower, but it increases in the Great Plains and in the monsoon area of the Southwest.

4.2 Extremes

Daily accumulations of precipitation were ranked (locally) for the period 1948-2004 (by season) and heavy precipitation days were defined as those in the upper 10% of the daily distribution. For these calculations we used daily precipitation time series for wet days (a wet day at a particular grid point is defined as a day with measurable precipitation exceeding a threshold of 1 mm day^{-1} at that gridpoint). Geographical maps of the threshold for ranked daily precipitation at the 90th percentile by season (not shown) reveal a marked annual cycle in the threshold in some regions. For example, in portions of the Pacific Northwest, northern California and along the Gulf Coast the threshold is at least two times higher during the winter (in excess of 25 mm) than during the summer (around

10 mm). The annual cycle is much weaker over the eastern United States, where precipitation occurs more regularly throughout the year.

The annual cycle of the fraction of total seasonal precipitation due to heavy (>90th percentile) precipitation days (not shown) is also large in areas with pronounced wet and dry seasons. For example, in the Southwest the fraction of total rainfall explained by heavy precipitation days drops substantially during the summer monsoon (JAS) compared to the other seasons. On the other hand, the annual cycle is much smaller in the eastern United States where it tends to rain more consistently throughout the year.

The total accumulated precipitation due to heavy (> 90th percentile) precipitation days has increased substantially (as much as 20%) over portions of the western and west-central United States during the past several decades (Fig. 5). These results are consistent with the observed changes in the mean frequency of measurable (> 1 mm) daily precipitation occurrence in the region (Fig. 4). They are also consistent with the results of earlier studies by Groisman et al. (1998, 2001, 2004, 2005). Since the threshold for ranked daily precipitation at the 90th percentile has not changed by more than a few millimeters at any given location during this five-decade period (not shown), this implies that the average intensity of extreme events on the tails of the distribution (i.e. the variance) is increasing in these regions.

5. Interannual Fluctuations

A classification of El Niño and La Niña episodes (section 2) was used to examine relationships between ENSO and interannual fluctuations in daily precipitation statistics in the United States. Composite mean differences of the frequency of measurable (> 1 mm) daily precipitation occurrence and of the total precipitation due to heavy (>90th percentile) precipitation days are shown in Figs. 6 and 7, respectively. Results are shown by season for moderate /strong (hereafter m/s) El Niño and m/s La Niña episodes, which are defined as those with ONI > +1.0 (ONI <-1.0) (see section 2). The numbers of El Niño and La Niña episodes in each composite are indicated on the figures, and areas where the composite differences are significant at the 95% level are indicated by shading.

The Southwest (Pacific Northwest and Ohio Valley) averages up to 15% more (fewer) wet days per winter season during m/s El Niño compared to m/s La Niña (Fig. 6). Similar features are observed during the transition seasons, though the patterns are weaker. During the summer the northern United States averages up to 15% more wet days per season during m/s El Niño compared to m/s La Niña episodes.

Extreme events over portions of California and the Southeast contribute an additional 50 mm or more per winter season during m/s El Niño compared to m/s La Niña (Fig. 7); this is consistent with the changes in the frequency of measurable daily precipitation occurrence (Fig. 6). Decreases of up to 50 mm are observed in the Ohio Valley. During NH summer the heavy precipitation days contribute 25 mm or more per m/s El Niño over portions of the Northern Plains and Midwest.

The above features generally agree with previous studies (e.g. Kousky et al. 1984; Ropelewski and Halpert 1987; Aceituno 1988; Kiladis and Diaz 1989) that have highlighted regional precipitation anomaly patterns associated with ENSO events. We note that there is considerable non-linearity in ENSO’s effect on heavy precipitation frequency over the contiguous U.S. (e.g. Gershunov 1998), suggesting that there may be better ways to examine the ENSO signal than composite differences.

6.0 Interdecadal Fluctuations

In anticipation of section 7, here we examine the frequency distributions of daily precipitation for two periods, namely 1948-1975 and 1976-2004, chosen to separate the well documented climate shift towards more El-Niño-like conditions after 1975. We examined the conterminous United States as a whole, as well as selected regions, and individual locations. Because the conterminous United States is a large region, the area mean daily accumulations are small (on the order of a few mm or less), but the frequency of measurable (> 1 mm) daily precipitation occurrence is large because precipitation is almost always occurring somewhere in the United States. The frequency distributions are for all days of the year, and results are based on the average number of wet days per year in each precipitation class. The precipitation classes are 0-1 mm, 1.01-2 mm, etc.

For the conterminous United States there have been increases in the frequency of heavy precipitation days (all thresholds exceeding 2 mm day^{-1}) and decreases in the frequency of light precipitation days (thresholds less than 2 mm day^{-1}) and days without precipitation during the recent (1976-2004) period when compared to the earlier (1948-1975) period (Fig. 8). It is important to note that these increases have not been uniform. Notably, the largest increases (up to 20% when expressed as a fraction of the total number of days in a particular interval) are for the extreme events. The change in shape of the distributions between the two periods (Fig. 8c) indicates that the increase in extreme events is associated with increased variability of daily precipitation. These results are consistent with studies of long-term trends that have shown that areas with increases in daily rainfall have experienced increases in extreme events (e.g. Karl and Knight 1998; Groisman et al. 1998, 2001, 2004, 2005).

In addition to the frequency distributions for the conterminous United States as a whole, we also examined the distributions for specific locations and for selected regions. Increases in the frequency of heavy precipitation days have occurred in many areas of the country since the mid-1970s, especially in the west. In contrast to the area average results for the entire United States (Fig. 8), the frequency distributions for individual locations and for small regions have more dry days and more extremely wet days; consequently, the relative changes between the two periods are larger than for the area average results. In our future work we will examine the frequency distributions in more detail, with emphasis on the mechanisms for these fluctuations.

Overall, these results are consistent with previous studies that have reported interdecadal variations of precipitation over western portions of the conterminous United States that are tied to interdecadal shifts of global atmospheric circulation and SST anomaly patterns (e.g. Higgins et al. 2000a), suggesting that the precipitation fluctuations are at least partly due to low-frequency climate processes on the global scale (e.g. Cayan et al. 1998; Gershunov and Cayan 2003).

7. Relationships to Climate Variability

Relationships between the PDO, AO, and long-term (interdecadal) fluctuations in the frequency of daily precipitation occurrence are estimated quantitatively using the method outlined in section 2. Changes in the frequency of measurable (> 1 mm) daily precipitation occurrence (Fig. 9) and in the total accumulated precipitation per year for all wet days (Fig. 11) and for heavy (> 90th percentile) precipitation days (Fig. 12) are based on differences between the periods (1976-2004) and (1948-1975) at each gridpoint over the United States. Areas where the changes are significant at the 95% level are indicated by shading on each figure.

Observed changes in the frequency of measurable daily precipitation occurrence (Fig. 9a) are largest over the western US, where increases exceed 5% of the number of days in a year. The PDO-related (Fig. 9b) changes are substantial, and explain about half of the observed increase over the western half of the Nation. The residual change (Fig. 9d), obtained by removing the PDO-related (Fig. 9b) and AO-related (Fig. 9c) changes (Fig. 9a) is generally small and mainly confined to the Intermountain West. Recall that the residual is attributable to other possible factors including (1) random chance, (2) poorly understood episodic phenomena (including other forms of natural climate variability and possible interactions of the effects of the main climate modes), (3) changes in the observing system, (4) global warming, and (5) anthropogenic influences.

The results shown in Fig. 9 are in doubt in areas of the Intermountain West at locations where significant changes in the observing system have occurred during the period of record. A time series of the annual average number of daily station reports for the northern Rockies (115°W-105°W, 40°N-48°N) during the period 1948-2004 confirms that the station counts increased with the introduction of the SNOpack TELemetry (SNOTEL) data (NCDC 2002a) starting in 1978 and again with the introduction of the River Forecast Center (RFC) data (NCDC 2002b) starting in 1992 (Fig. 10a). Both networks emphasize mountain / alpine locations where precipitation tends to occur more frequently than in adjacent valleys. As a consequence, there is an increase in the frequency of measurable daily precipitation for the gridded analysis during the more recent period. The corresponding time series of the annual frequency of measurable (> 1 mm) daily precipitation occurrence, expressed as a fraction of the number of days in a year (Fig. 10b), exhibits a trend that is similar to that in the time series of station counts for this region (Fig. 10a). Overall, these results indicate that the change in the frequency of measurable daily precipitation occurrence is at least partly due to changes in the station network. In section 7.1 we use a different precipitation dataset (the Hourly Precipitation Dataset of Higgins et al. 1996) to examine the possible influences of spatial homogeneity and temporal continuity on the results.

Changes in the frequency of measurable (> 1 mm) daily precipitation occurrence generally correspond to changes in the total accumulated precipitation per year (Fig. 11), with substantial increases over most of the US, except in portions of the Southeast, northern tier-of-states, and along the Pacific Northwest Coast. Much of the change between the two periods is explained by the PDO (Fig. 11b). Relationships with the AO are weak (Fig. 11c) and not statistically significant.

Increases along the Gulf Coast exceed 100 mm (4 inches) per year at some locations (Fig. 11a). Since the mean annual precipitation totals are as large as 1500 mm in this region (Fig. 2), this increase represents roughly 5%-10% of the mean annual rainfall. Increases exceeding 50 mm are also observed at many locations in the central and western US (Fig. 11a), and again this represents a 5%-10% increase.

Previous studies of long-term trends in precipitation have shown that in many regions where average rainfall has been increasing, there have also been trends in extreme precipitation events (e.g. US CCSP 2003). A comparison of the patterns in Figs. 11a and 12a confirms that this is also true when differences between the two periods (1948-1975) and (1976-2004) are considered.

The seasonality of the changes documented in Figs. 11 and 12 has also been examined. The changes along the southern tier-of-states have primarily occurred during the winter and spring seasons (not shown), consistent with the relative increase in El Niño events, and consequently El Niño-related influences on precipitation during the more recent period.

7.1 Influence of spatial and temporal continuity

The Hourly Precipitation Database (HPD) of Higgins et al (1996) does not include the SNOTEL or the RFC stations, and hence is a more spatially and temporally homogeneous data set than the URD. The HPD still suffers from some incomplete station records, but to a lesser extent than the URD (a factor we intend to address in follow-on studies).

A reexamination of the annual frequency of measurable daily precipitation occurrence for the Northern Rockies (Fig. 13b) shows a slow steady increase since the late 1940s, though the frequencies are lower than in the URD (Fig. 10b) as would be expected due to the lack of mountain sites in the HPD. Overall there is an increase of roughly 6% (22 days per year) from the 1940s to the 1990s. An examination of the station counts in this region from the HPD (Fig. 13a) shows that there are no large jumps in the late 1970s or early 1990s as in the URD (Fig. 10a), though there is an unexplained change during the 1950s (Fig. 13a). However, the relatively stable station counts since then lend credence to the conclusion that the annual frequency of measurable daily precipitation occurrence has increased in this region (Fig. 13b).

The HPD was also used to reexamine the relationships between the PDO and AO, and changes in the annual frequency of measurable (> 1 mm) daily precipitation occurrence expressed as a fraction of the number of days in the year (Fig. 14a). The HPD pattern is similar to the URD pattern (Fig. 9a), except that the differences in mountainous areas of the western United States are somewhat lower, averaging around 2-3% (7-11 days). Again the PDO-related changes are significant in the western United States (Fig. 14b) while the AO-related changes are negligible (Fig. 14c). The residual (Fig. 14d) is a rather uniform increase of roughly 1% (~ 4 days) over most of the nation, though these changes are significant in limited portions of the west-central United States..

The HPD was also used to examine changes in the accumulated precipitation per year due to wet days (not shown) and due to heavy (>90th percentile) precipitation days (not shown). The patterns are qualitatively similar to those shown in Figs. 11 and 12, respectively, and the quantitative comparison is quite good for the eastern two-thirds of the US. Additional details (including the seasonality of these changes) will be examined after the HPD and URD datasets are reanalyzed using temporally complete station records.

8. Summary and Future Plans

Fluctuations in the frequency of daily precipitation occurrence over the United States during the period 1948-2004 were identified and linked to some leading patterns of climate variability. The ENSO phenomena were implicated in interannual fluctuations while the PDO (and to a lesser extent the AO) were implicated in long-term (interdecadal) fluctuations. The analysis of long-term changes confirms that there have been increases in the annual frequency of wet days and heavy precipitation days, and in the mean daily (and annual) precipitation over the past several decades, though these changes have not been uniform. Increases in the annual number of wet days average 5-10 days per year in the eastern United States and 10-15 days per year in the western half of the nation. We are more confident of the results in the eastern half of the nation due to the relative stability of the station network during the period of record. The PDO accounts for about half of the total observed change in the Intermountain West, while the combination of the PDO and the AO account for between a quarter and a half of the change in the Southeast (though the AO results are generally not statistically significant). The residual change is interpreted as the integrated effect of other patterns of climate variability, random noise, changes in the raingauge network, global warming, anthropogenic influences, and other possible influences.

Because the interdecadal fluctuations in the frequency of daily precipitation occurrence and in the intensity of daily precipitation are linked to changes in the global scale circulation and sea surface temperatures associated with the PDO, the results imply that a significant portion of the skill of climate models in anticipating these fluctuations will likely arise from an ability to forecast the temporal and spatial variability of the interdecadal shifts in tropical precipitation and associated teleconnection patterns into midlatitudes.

A key challenge is to develop models that capture this climate variability and the statistics of daily precipitation as found in nature. Diagnostic studies that compare state-of-the-art climate model simulations and observations can then be used to address a number of basic questions concerning the extreme events:

Do climate models simulate the observed linkages between (interannual and interdecadal) climate variability and changes in the frequency of daily precipitation extremes?

Are changes in the statistics of extreme events predictable?

Does the simulated frequency of daily precipitation extremes lie within or outside the range of natural variability?

Continued progress will require advancements in scientific understanding of the climate variations themselves and in quantitative estimates of how these variations alter the frequency of daily precipitation occurrence. Improved climate-quality daily precipitation data sets are essential. Ultimately, these studies should lead to improved forecasts of precipitation extremes.

One of the key issues raised in this study concerned changes in the observational data base over the western United States during the period of record. By comparison of the URD (less homogeneous in space and time) to the HPD (more homogeneous in space and time), we were able to obtain an improved quantitative estimate of the daily precipitation fluctuations in that region. In the future, we will improve our quantitative estimates further by requiring that station records be sufficiently complete (e.g. 80% or greater) prior to the objective analysis. In the future we also plan to apply the method used in section 7 to a study of long-term fluctuations in other types of extreme weather events (e.g. daytime maximum temperature, nighttime minimum temperature). This will include assessments of the ability of state-of-the-art climate models to simulate observed fluctuations in weather extremes during the 20th century. Models are also getting to the point that it will be useful to examine the regionality of the fluctuations in extreme weather events in more detail than has been done in the past.

9. Acknowledgments

The authors gratefully acknowledge the assistance of CPC personnel who helped us pull together the gauge precipitation and reanalysis datasets used in this study, including Drs. Pingping Xie and Muthuvel Chelliah. We also thank Dr. Vernon Kousky, Mike Halpert and four anonymous reviewers for insightful comments on early drafts of this work.

10. References

Aceituno, P., 1988: On the functioning of the Southern Oscillation in the South American sector. *Mon. Wea. Rev*., **116**, 505-525.

Ambaum, M. H. P., B. J. Hoskins, and D. B. Stephenson, 2001: Arctic Oscillation or North Atlantic Oscillation? *J. Climate*, **14**, 3495-3507).

Arkin, P. A., 1982: The relationship between interannual variability in the 200 mb tropical wind field and the Southern Oscillation. *Mon. Wea. Rev*., **110**, 1393-1404.

Berlage, H. P., 1966: The Southern Oscillation and world weather. *K. Ned. Meteorol. Inst. Meded. Verh.*, **88**, 152 pp.

Bhlame, H. N., D. A. Mooley, and S. K., Jadhav, 1983: Fluctuations in the drought / flood area over India and relationships with the Southern Oscillation. *Mon. Wea. Rev.*, **111**, 86-94.

Bjerknes, J., 1966: A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus*, **18**, 820-829.

-------------, 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev*., **97**, 163-172.

Caviedes, C. N., 1973: Secas and El Niño: Two simultaneous climatological hazards in South America. *Proc. Assoc. Amer. Geogr*., **5**, 44-49.

Cayan, D. R., M. Dettinger, H. Diaz and N.E. Graham, 1998: Decadal variability of precipitation over western North America. *J. Climate*, **11,** 3148-3166.

-------------, Redmond, K. T. and L. G. Riddle, 1999: ENSO and hydrologic extremes in the western United States. *J. Climate*, **12**, 2881-2893.

Changnon, S.A., 1998: Comments on "Secular trends of precipitation amount, frequency, and intensity in the United States." *Bull. Amer. Met. Soc.*, **79**, 2550-2552.

Charba, J. P., A. W. Harrell III and A. C. Lackner III, 1992: A monthly precipitation amount climatology derived from published atlas maps: Development of a digital data base. *TDL Office Note 92-7*, NOAA, U.S. Department of Commerce, 20 pp.

Cressman, G. P., 1959: An operational objective analysis system. *Mon. Wea. Rev.*, **87**, 367-374.

Dettinger, M.D., D. R. Cayan, H. F. Diaz, and D. Meko, 1998: North-south precipitation patterns in western North America on interannual-to-decadal time scales: *J. Climate,* **11**, 3095-3111.

Easterling, D. R., J. L. Evans, P. Ya. Groisman, T. R. Karl, K. E. Kunkel, and P. Ambenje, 2000: Observed variability and trends in extreme climate events: A Brief Review, *Bull. Amer. Met. Soc.*, **81**, 417-425.

Ebbesmeyer, C.C., D. R. Cayan, D. R. Milan, F. H. Nichols, D. H. Peterson, and K. T. Redmond, 1991: 1976 step in the Pacific climate: Forty environmental changes between 1968-1975 and 1977-1984. *Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop*, California Department of Water Resources. Interagency Ecological Studies Program. Technical Report 26, 115-126.

Frederiksen, C.S. and X. Zheng, 2004: Variability of Seasonal Mean Fields Arising from Intraseasonal Variability : Part 2, Application to NH Winter Circulations. Climate *Dynamics*, **23**, 193-206.

Gershunov, A., 1998: ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: Implications for long-range predictability, *J. Climate*, **11**, 3192-3203.

-------------, and T. Barnett, 1998a: ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: Observations and model results. *J. Climate,* **11,** 1575– 1586.

-------------, and -------------, 1998b: Interdecadal modulation of ENSO teleconnections. *Bull. Amer. Meteor. Soc.,* **79,** 2715–2725.

-------------, -------------, and D. Cayan, 1999: North Pacific Interdecadal Oscillation seen as factor in ENSO-related North American climate anomalies. *Eos, Trans. Amer. Geophys. Union*, **80,** 25–30.

-------------, and D. Cayan, 2003: Heavy daily precipitation frequency over the contiguous United States: Sources of climatic variability and seasonal predictability. *J. Climate*, **16**, 2652-2765

Glahn, H. R., T. L. Chambers, W. S. Richardson, and H. P. Perrotti, 1985: Objective map analysis for the local AFOS MOS Program. *NOAA Technical Memorandum NWS TDL 75*, NOAA, U. S. Department of Commerce, 34 pp.

Graham, N. E., 1994: Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: Observations and model results. *Climate Dyn.*, **10**, 135-162.

Groisman, P. Ya, and Coauthors, 1998: Changes in the probability of heavy precipitation: Important indicators of climatic change. *Climatic Change,* **42,** 243–283.

-------------, R. W. Knight, and T. R. Karl, 2001: Heavy precipitation and high streamflow in the contiguous United States: Trends in the 20th century. *Bull. Amer. Meteor. Soc.,* **82,** 219–246.

-------------, R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore 2004: Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations, *J. Hydrometeor*, **5**, 65-84.

-------------, -------------, -------------, -------------, G. Hegerl, and V. Razuvaev, 2005: Trends in intense precipitation in the climate record. *J. Climate*, **18**, 1326-1350.

Gu, D.F. and S.G.H. Philander, 1997: Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science*, **275**, 805-807.

Halpert, M. S. and C. F. Ropelewski, 1992: Surface temperature patterns associated with the Southern Oscillation. *J. Climate*, **5**, 577-593.

Hare, S.R., and N.J. Mantua, 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography*, **47**,103-145.

Hastenrath, S and L. Heller, 1977: Dynamics of climate hazards in northeast Brazil. *Quart. J. Roy. Meteor. Soc.*, **103**, 77-92.

Held, I. M. and I. S. Kang, 1987: Barotropic models of the extratropical response to El Niño. *J. Atmos. Sci.*, **44**, 3576-3586.

Higgins, R. W., A. Leetmaa, Y. Xue and A Barnston, 2000a: Dominant factors influencing the seasonal predictability of United States precipitation and surface air temperature. *J. Climate*, **13**, 3994-4017.

-------------, W. Shi, E. Yarosh and R. Joyce, 2000b: Improved United States Precipitation Quality Control System and Analysis. NCEP/Climate Prediction Center ATLAS No. 7, 40 pp. [Available from Climate Prediction Center, 5200 Auth Road, Camp Springs, MD, 20746].

-------------, J. E. Janowiak and Y. Yao, 1996: A gridded hourly precipitation data base for the United States (1963-1993). NCEP/Climate Prediction Center ATLAS 1, 47 pp.

Hoerling, M. P., J. W. Hurrell, and T. Xu, 2001: Tropical origins for recent north Atlantic climate change. *Science*, **292**, 90-92.

Horel, J. D. and J. M. Wallace, 1981: Planetary scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813-829.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation region temperatures and precipitation. *Science*, **269**, 676-679.

Karl, T.R., and R. W. Knight, and N. Plummer, 1995: Trends in high-frequency climate variability in the twentieth century. *Nature*, **377**, 217-220.

-------------, and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.*, **79,** 1107–1119.

Karoly, D. R., A. Plumb, and M. Ting, 1989: Examples of the horizontal propagation of quasi-stationary waves. *J. Atmos. Sci.*, **46**, 2802-2811.

Kiladis, G. N and H. F. Diaz, 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. *J. Climate*, **2**, 1069-1090.

Kousky, V.E., M.T. Kayano, and I.F.A Cavalcanti, 1984: The Southern Oscillation: Oceanic-atmospheric circulation changes and related rainfall anomalies. *Tellus*, **36A**, 490-504.

Kunkel, K. E., K. Andsager and D. R. Easterling, 1999: Long-Term Trends in Extreme Precipitation Events over the Conterminous United States and Canada. *J. Climate*, **12**, 2515-2527.

Latif, M. and T.P. Barnett, 1994: Causes of decadal climate variability over the north Pacific and North America. *Science*, **266**, 634-637.

Livezey, R. E., 1995: Field intercomparison. *An Analysis of Climate Variability Applications of Statistical Techniques*, H. Von Storch and A. Navarra, Eds., Springer-Verlag, 159-176.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.*,**78**, 1069-1079.

National Climatic Data Center, 2002a: Data Documentation for Data Set 6430: USDA/NRCS SNOTEL - Daily Data, Text Reports. Available from National Climatic Data Center 151 Patton Ave, Asheville, NC 28801-5001 USA, 11 pp.

National Climatic Data Center, 2002b: Data Documentation for Data Set 6410: River Forecast Center Network. Available from National Climatic Data Center 151 Patton Ave, Asheville, NC 28801-5001 USA, 5 pp.

Nita, T., and S. Yamada, 1989: Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation. *J. Meteor. Soc. Japan*, 67, 375-383.

Rasmusson, E. M., T. H. Carpenter, 1983: The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon. Wea. Rev.*, **111**, 517–528.

Rasmusson, E. M. and K. Mo, 1993: Linkages between 200-mb tropical and extratropical circulation anomalies during the 1986-1989 ENSO cycle. *J. Climate*, **6**, 595-616.

Ropelewski, C. F., and M. S. Halpert, 1986: North American precipitation and temperature patterns associated with the El Niño/ Southern Oscillation (ENSO). *Mon. Wea. Rev.*, 114, 2352-2362.

-------------, and -------------, 1987: Global and regional scale precipitation patterns associated with the El Niño/ Southern Oscillation. *Mon. Wea. Rev.*, **115**, 1606-1626.

Simmons, A. J., J. M. Wallace, and G. W. Branstator, 1983: Barotropic wave propagation and instability, and atmospheric teleconnection patterns. *J. Atmos. Sci.*, **40**, 1363-1392.

Smith, T. M., and R. W. Reynolds, 2003: Extended Reconstruction of Global Sea Surface Temperatures Based on COADS Data (1854–1997). *J. Climate,* **16**, 1495-1510.

Thompson, D. W. J., and J. M. Wallace, 1998: The arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.,* **25,** 1297–1300.

-------------, and -------------, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate*, **13,** 1000–1016.

-------------, and -------------, 2001: Regional climate impacts of the northern hemisphere annular mode. *Science*, **293**, 85–89.

-------------, -------------, and G. C. Hegerl, 2000: Annular modes in the extratropical circulation. Part II: Trends. *J. Climate,* **13,** 1018–1036.

Trenberth, K. E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Amer. Meteor. Soc.*, **71**, 988–993.

Trenberth, K. E and J. W. Hurrell, 1994: Decadal atmospheric-ocean variations in the Pacific. *Climate Dyn.*, **9**, 303-309.

Troup, A. J., 1965: The Southern Oscillation. *Quart. J. Roy. Meteor. Soc.*, **91**, 490-506.

USCCSP, 2003: *Strategic Plan for the U.S. Climate Change Science Program*. Climate Change Science Program and Subcommittee on Global Change Research. Climate Change Science Program Office, 1717 Pennsylvania Avenue, NW, Suite 250, Washington, DC 20006.

Walker, G. T., and E. W. Bliss, 1932. World Weather V. *Mem. Roy. Meteor. Soc.*, **4**, 53-84.

Wallace, J. M., 2000: North Atlantic Oscillation / Northern Hemisphere annular mode: Two paradigms – one phenomenon. *Quart. J. Roy. Meteor. Soc.*, **126**, 791-806.

Zhang, Y., J. M. Wallace, and D. S. Battisti, 1997: ENSO-like interdecadal variability: 1900-93. *J. Clim.*, **10**, 1004-1020.

11. Figure Captions

Figure 1. ONI, PDO and AO indices (1948-2004). Each index has been normalized by the annual standard deviation in the index. An 11-yr running mean (solid line) is also shown on each panel.

Figure 2. The mean (1948-2004) annual precipitation (units: mm) based on the daily precipitation analysis for the United States.

Figure 3. Mean (1948-2004) annual frequency of daily precipitation occurrence at thresholds of (a) > 1 mm and (b) > 25 mm, expressed as a percentage of the number of days in a year (units: percent).

Figure 4. Mean frequency of measurable (> 1 mm) daily precipitation occurrence by decade (1950s, 1960s, 1980s, 1980s and 1990s) expressed as a percent departure from the mean frequency of measurable daily precipitation occurrence for 1948-2004 (units: percent).

Figure 5. Total accumulated precipitation due to heavy (> 90th percentile) precipitation days by decade (1950's, 1960's, 1970's, 1980's, 1990's) expressed as a percent departure from the total accumulated precipitation due to heavy (>90th percentile) precipitation days for the entire period 1948-2004 (units: percent).

Figure 6. Composite difference of the mean frequency of measurable (> 1 mm) daily precipitation occurrence between m/s warm (El Niño) and m/s cold (La Niña) episodes by season (contours). Results are expressed as a percentage of the number of days in the season (units: percent). The contour interval is 5% and the zero contour has been omitted. Shading indicates areas where the composite differences are significant at the 95% level. Results are based on daily data for the period 1948-2004. The number of warm and cold episodes in each composite is indicated on the figure.

Figure 7. Composite difference of the accumulated precipitation per year due to heavy (> 90th percentile) precipitation days (units: mm) between m/s warm (El Niño) and m/s cold (La Niña) by season (contours). The contour interval is 25 mm and the 0 contour has been omitted. Shading indicates areas where the composite differences are significant at the 95% level. Results are based on daily data for the period 1948-2004. The number of warm and cold episodes in each composite is indicated on the figure.

Figure 8. Frequency distributions of daily precipitation for the conterminous United States for (a) 1948-1975 and (b) 1976-2004 and (c) the difference [(1976-2004)-(1948-1975)]. Results are based on all days of the year and are annual averages for each period. The precipitation classes are 0-1 mm, 1.01-2 mm, 2.01-3 mm, etc. as indicated along the abscissa. In (c) the dark (light) shaded areas indicate increases (decreases) in the annual number of events for each precipitation class.

Figure 9 Percent change of the mean frequency of measurable (> 1 mm) daily precipitation occurrence between the period (1976-2004) and the period (1948-1975). Results are expressed as a fraction of the number of days in a year (units: percent). The contours are -5%, -3%, -1%, 1%, 3% and 5%. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.

Figure 10. (a) Time series of the annual average number of daily station reports for the northern Rockies (115W-105W, 40N-48N) during the period 1948-2004 from the Unified Raingauge Database (URD). (b) Time series of the frequency of measurable (>1 mm) daily precipitation occurrence expressed as a percentage of the number of days in a year for the northern Rockies (115W-105W, 40N-48N).

Figure 11. Change of the total accumulated precipitation per year (units: mm/year) due to wet days (> 1 mm) between the period (1976-2004) and the period (1948-1975). The contours are -100 mm, -50 mm, -25mm, 25 mm, 50 mm and 100 mm. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.

Figure 12. Change of the total accumulated precipitation per year (units: mm/year) due to heavy (> 90th percentile) precipitation days between the period (1976-2004) and the period (1948-1975). The contours are -40 mm, -20 mm, -10 mm, 10 mm, 20 mm and 40 mm. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change

minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.

Figure 13. (a) Time series of the annual average number of daily station reports for the northern Rockies (115W-105W, 40N-48N) during the period 1948-1998 from the Hourly Precipitation Database(HPD). (b) Time series of the frequency of measurable (>1 mm) daily precipitation occurrence expressed as a percentage of the number of days in a year for the northern Rockies (115W-105W, 40N-48N) as obtained from the HPD.

Figure 14. Percent change of the mean frequency of measurable (> 1 mm) daily precipitation occurrence between the period (1976-1998) and the period (1948-1975) from the HPD. Results are expressed as a fraction of the number of days in a year (units: percent). The contours are -5%, -3%, -1%, 1%, 3% and 5%. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.

12. Table Captions

Table 1. Comparison of daily precipitation statistics for 10 major cities in the United States computed from raw station data and from the analyzed gridpoint nearest the city. Only annual statistics are shown.

Table 1. Comparison of daily precipitation statistics for 10 major cities in the United States computed from raw station data and from the analyzed gridpoint nearest the city. Only annual statistics are shown.

City	Annual Total Station (mm)	Annual Total Grid (mm)	Annual Frequency 1mm (25mm) Station (%)	Annual Frequency Grid (%)	Daily Variance Station (mm)	Daily Variance Grid (mm)
Chicago	903.1	899.7	27.6 (2.6)	34 (1.4)	55.7	30.9
Dallas	894.6	903.5	13.9 (2.9)	27.9 (1.9)	76.9	43.4
Miami	1473.2	1289.9	25.9 (4.2)	47.9 (1.8)	154.0	46.2
New York	1147.8	1165.7	26.4 (2.5)	37.4 (2.3)	79.3	47.2
San Francisco	513.8	542.4	13.3 (1.3)	17.3 (0.9)	29.4	22.9
Seattle	1930.1	1614.0	36.5 (1.4)	52.0 (2.5)	62.1	51.9
Boston	1089.9	1172.0	28.7 (3.5)	38.1 (2.3)	71.7	47.1
Los Angeles	313.7	401.8	6.8 (0.6)	10.6 (1.2)	23.5	25.3
Washington	979.2	1058.5	26.1 (2.8)	36.4 (1.8)	58.4	39.4
Phoenix	190.2	223.0	6.5 (0.3)	12.5 (0.1)	7.9	4.5

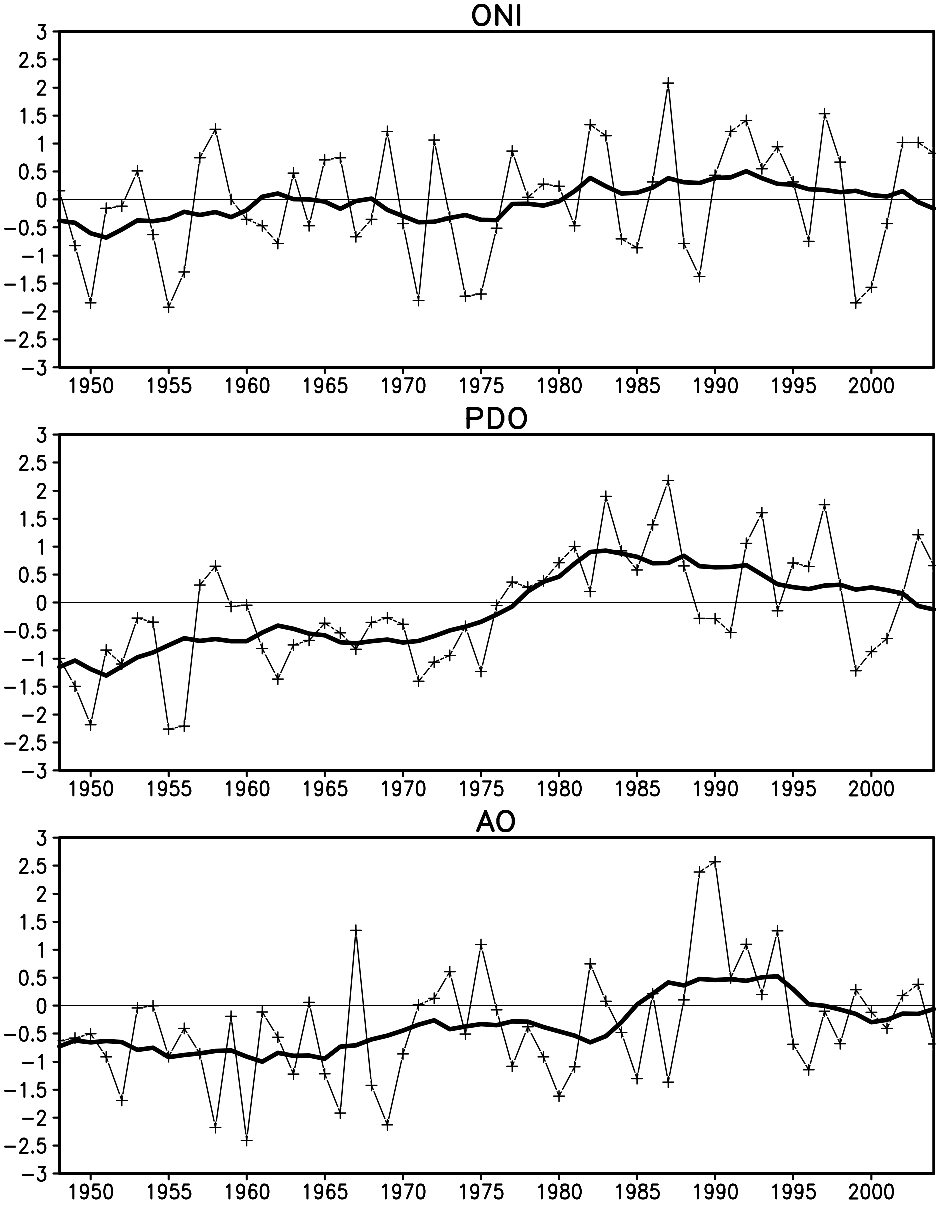


Figure 1. ONI, PDO and AO indices (1948-2004). Each index has been normalized by the annual standard deviation in the index. An 11-yr running mean (solid line) is also shown on each panel.

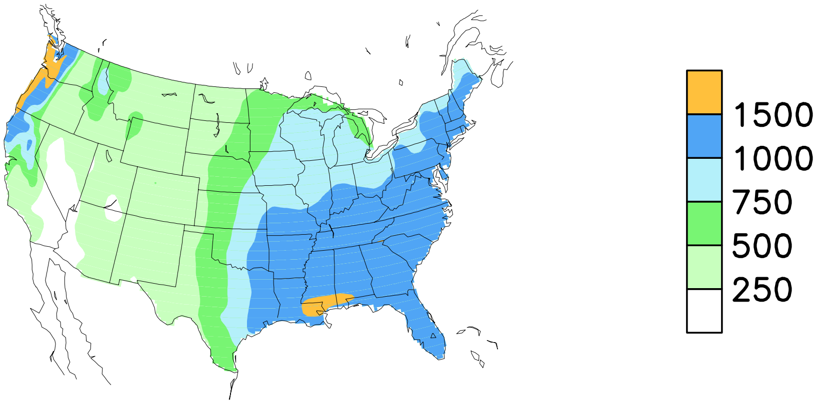
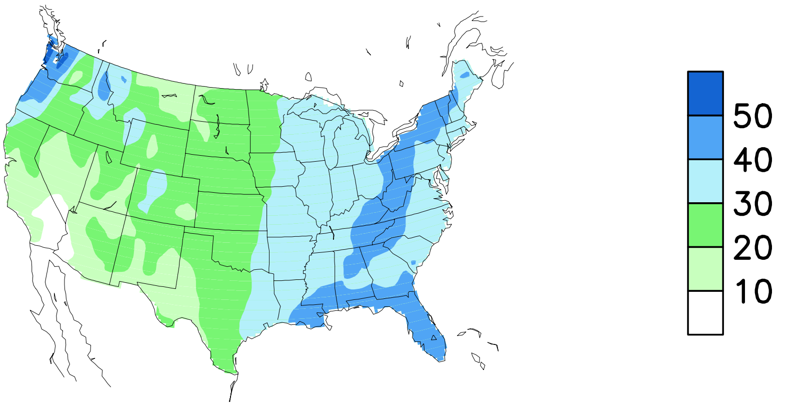
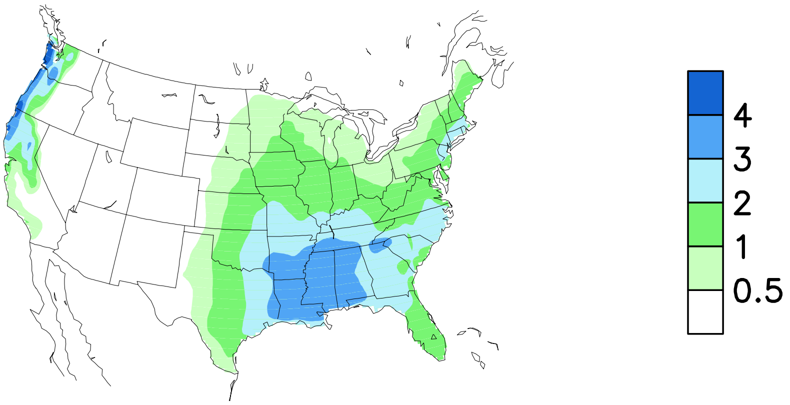


Figure 2. The mean (1948-2004) annual precipitation (units: mm) based on the daily precipitation analysis for the United States.



(a) > 1.0 mm



(b) > 25.0 mm

Figure 3. Mean (1948-2004) annual frequency of daily precipitation occurrence at thresholds of (a) > 1 mm and (b) > 25 mm, expressed as a percentage of the number of days in a year (units: percent).

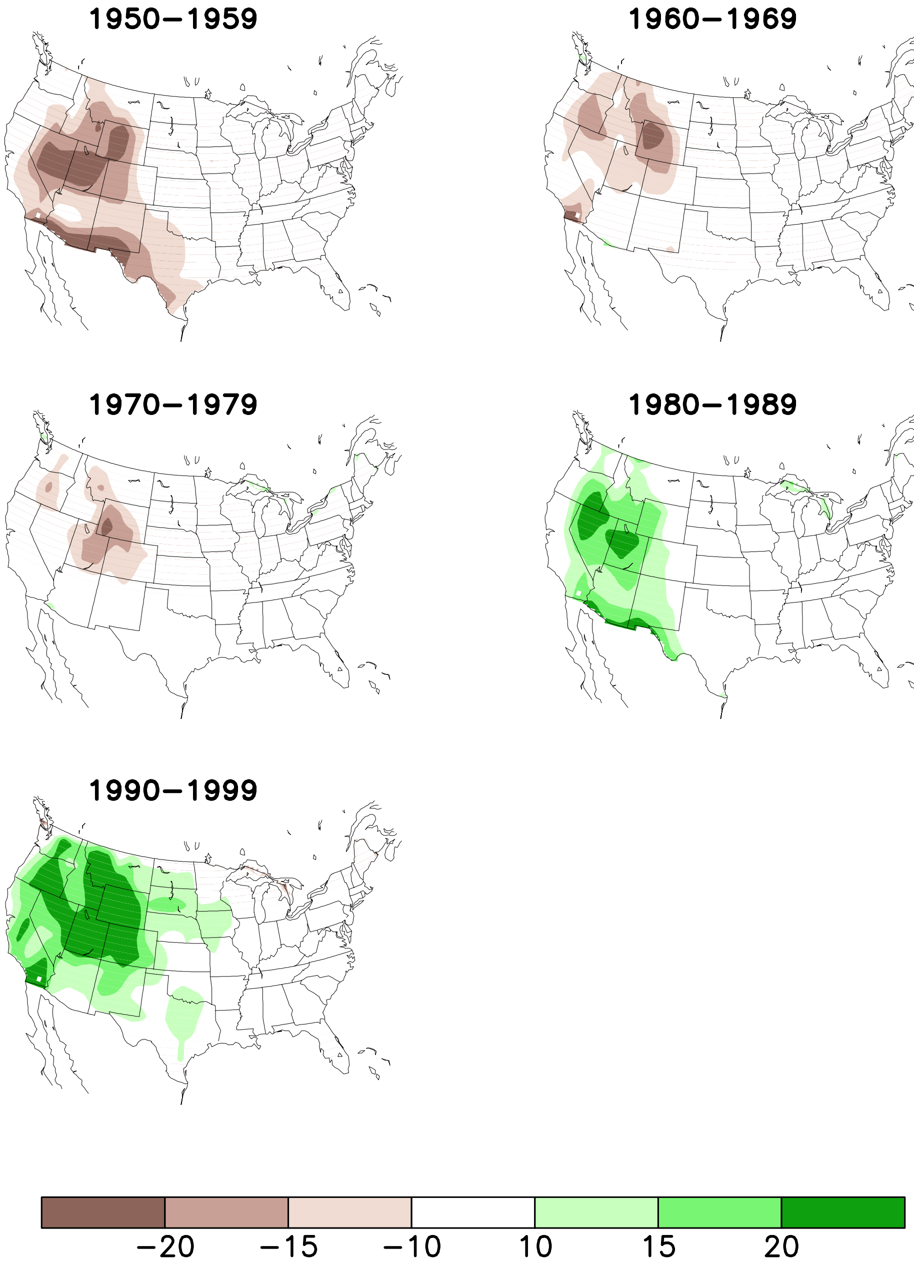


Figure 4. Mean frequency of measurable (> 1 mm) daily precipitation occurrence by decade (1950s, 1960s, 1980s, 1980s and 1990s) expressed as a percent departure from the mean frequency of measurable daily precipitation occurrence for 1948-2004 (units: percent).

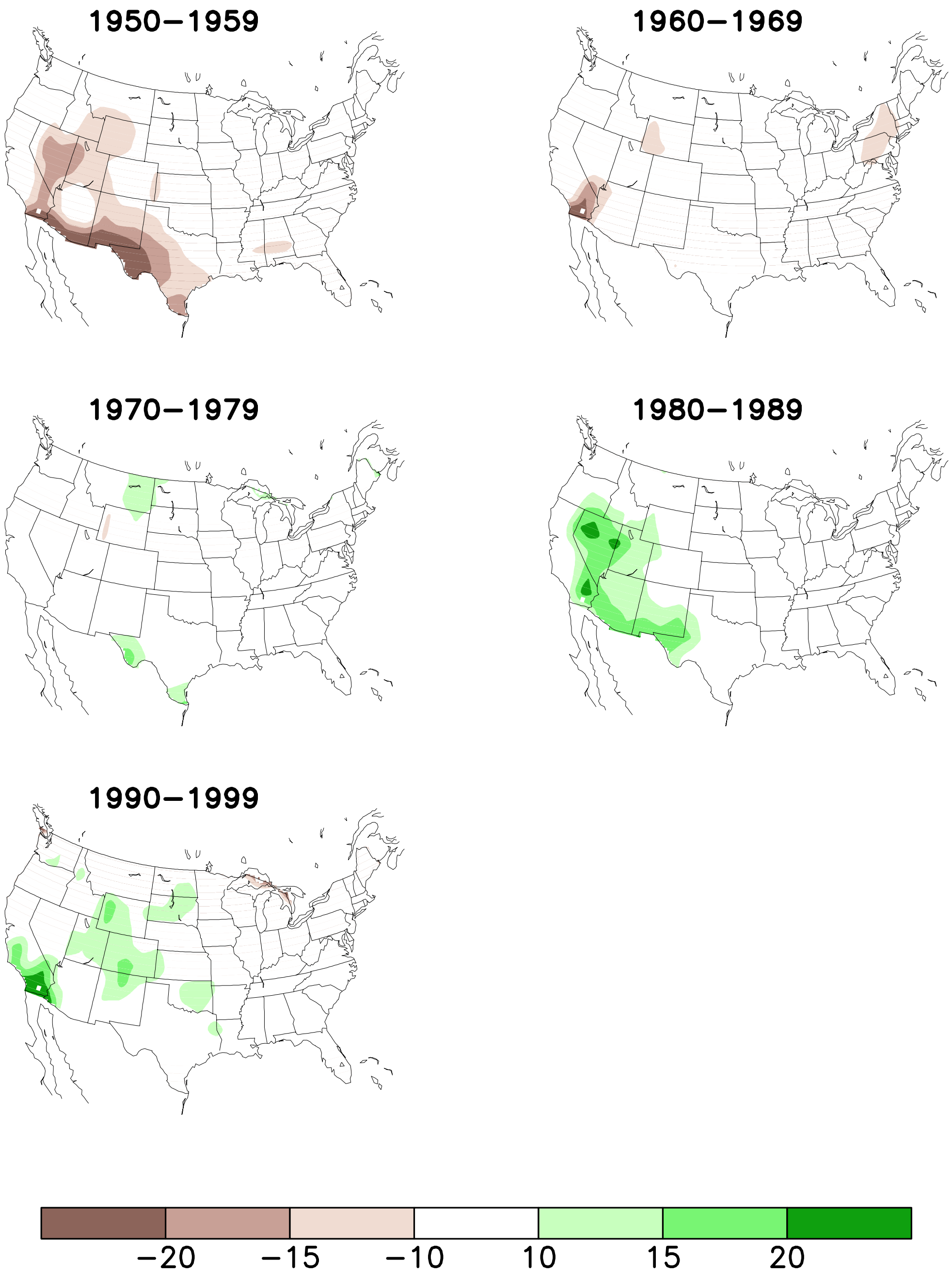
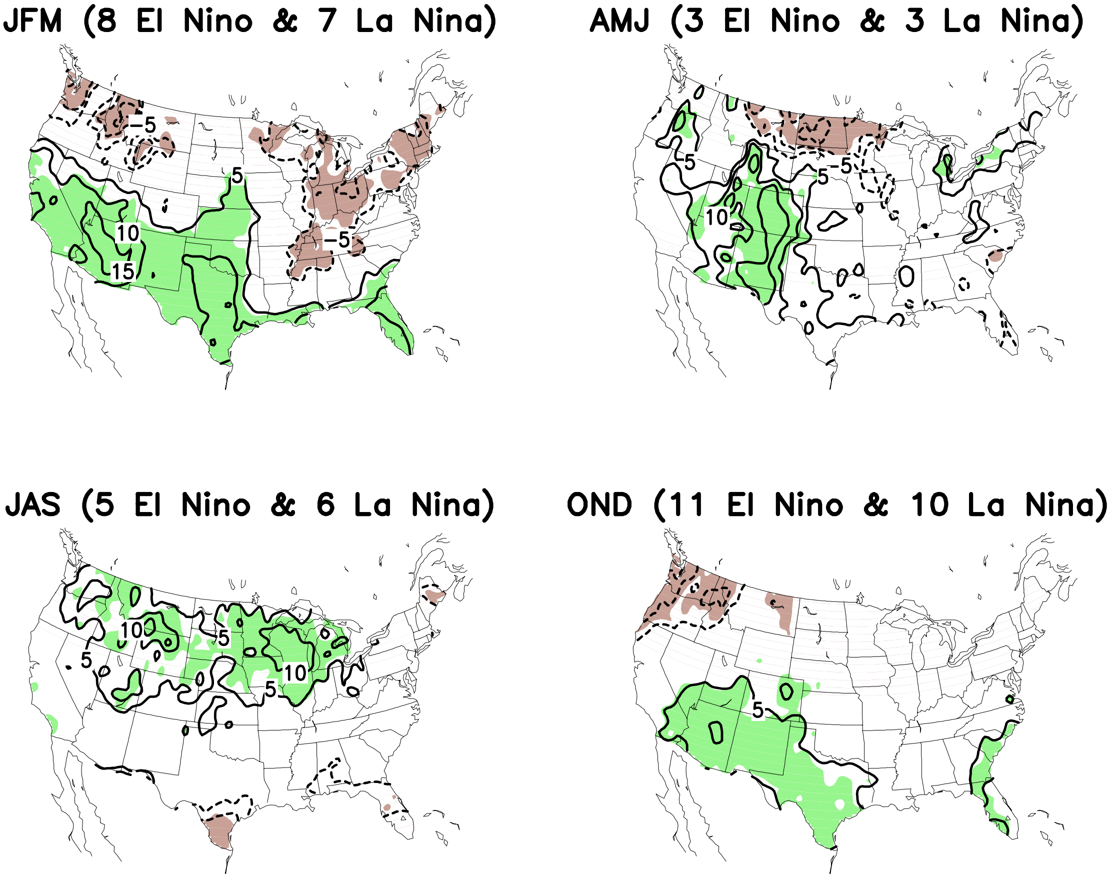


Figure 5. Total accumulated precipitation due to heavy (> 90th percentile) precipitation days by decade (1950's, 1960's, 1970's, 1980's, 1990's) expressed as a percent departure from the total accumulated precipitation due to heavy (>90th percentile) precipitation days for the entire period 1948-2004 (units: percent).



JFM (8 El Nino & 7 La Nina)

AMJ (3 El Nino & 3 La Nina)

JAS (5 El Nino & 6 La Nina)

OND (11 El Nino & 10 La Nina)

Figure 6. Composite difference of the mean frequency of measurable (> 1 mm) daily precipitation occurrence between m/s warm (El Niño) and m/s cold (La Niña) episodes by season (contours). Results are expressed as a percentage of the number of days in the season (units: percent). The contour interval is 5% and the zero contour has been omitted. Shading indicates areas where the composite differences are significant at the 95% level. Results are based on daily data for the period 1948-2004. The number of warm and cold episodes in each composite is indicated on the figure.

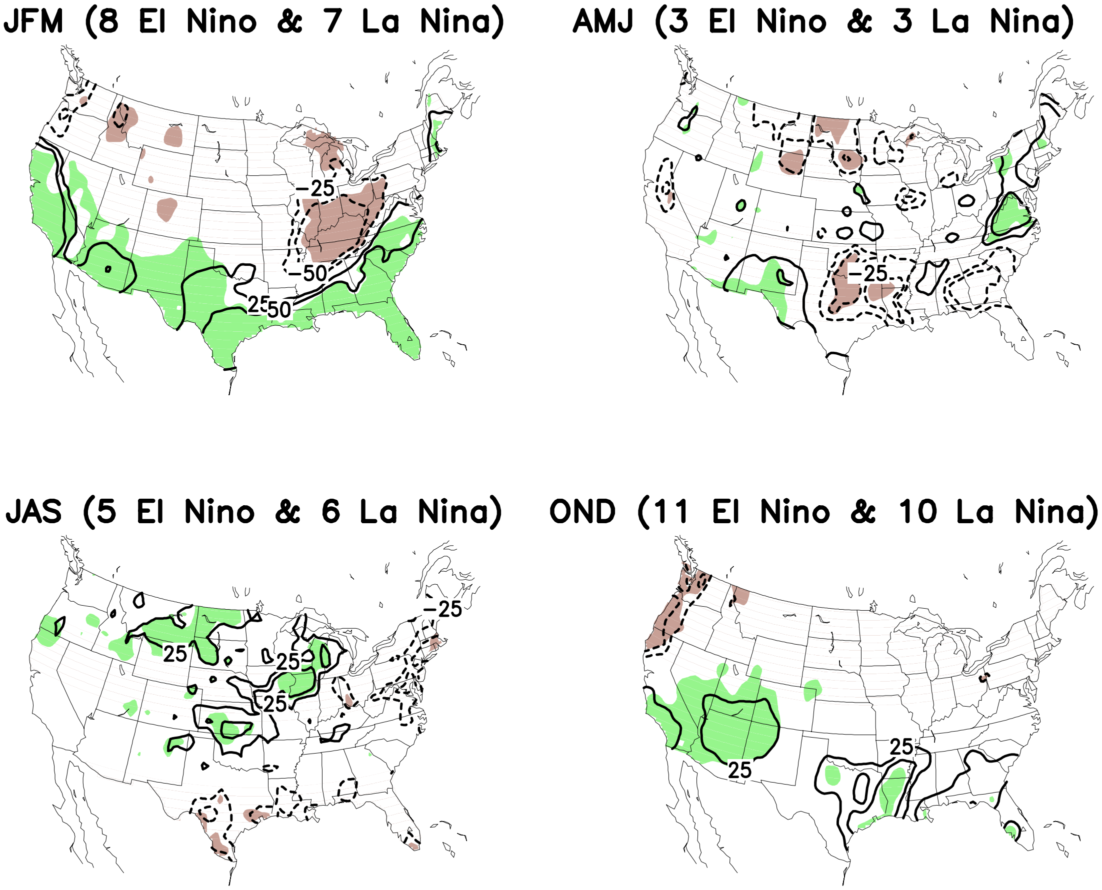


Figure 7. Composite difference of the accumulated precipitation per year due to heavy (> 90th percentile) precipitation days (units: mm) between m/s warm (El Niño) and m/s cold (La Niña) by season (contours). The contour interval is 25 mm and the 0 contour has been omitted. Shading indicates areas where the composite differences are significant at the 95% level. Results are based on daily data for the period 1948-2004. The number of warm and cold episodes in each composite is indicated on the figure.

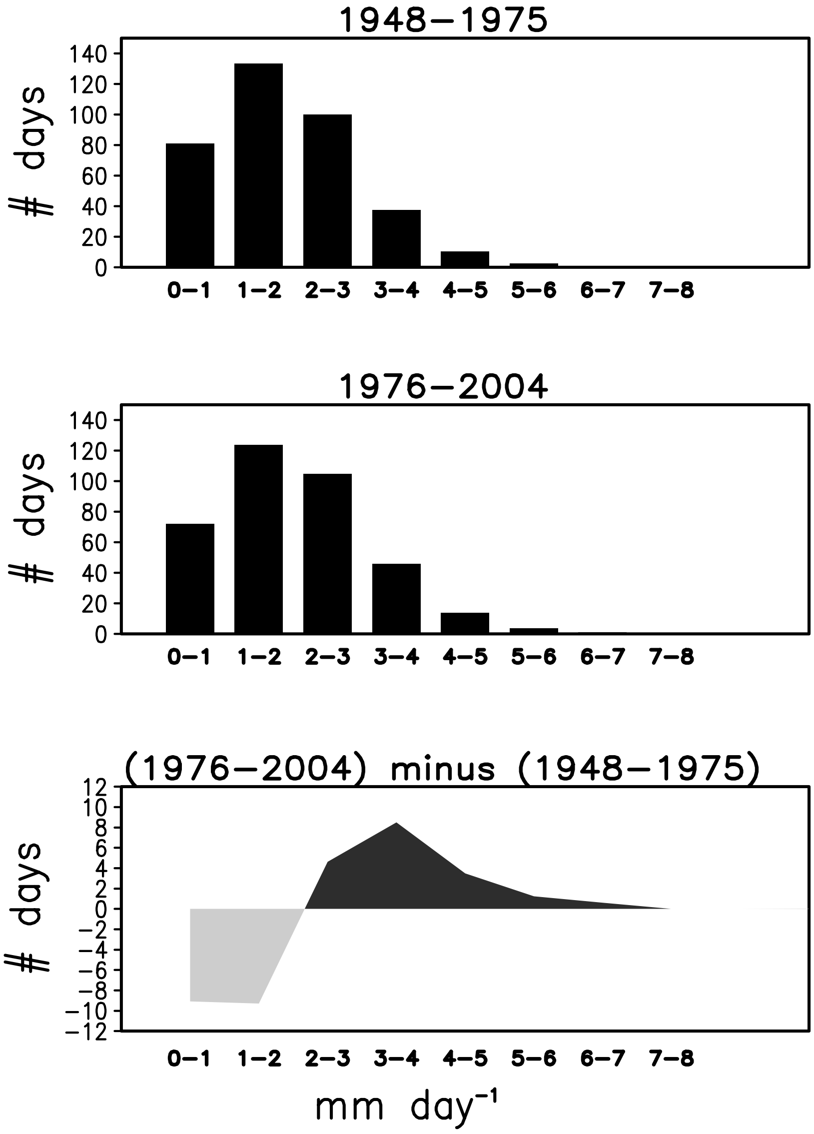


Figure 8. Frequency distributions of daily precipitation for the conterminous United States for (a) 1948-1975 and (b) 1976-2004 and (c) the difference [(1976-2004)-(1948-1975)]. Results are based on all days of the year and are annual averages for each period. The precipitation classes are 0-1 mm, 1.01-2 mm, 2.01-3 mm, etc. as indicated along the abscissa. In (c) the dark (light) shaded areas indicate increases (decreases) in the annual number of events for each precipitation class.

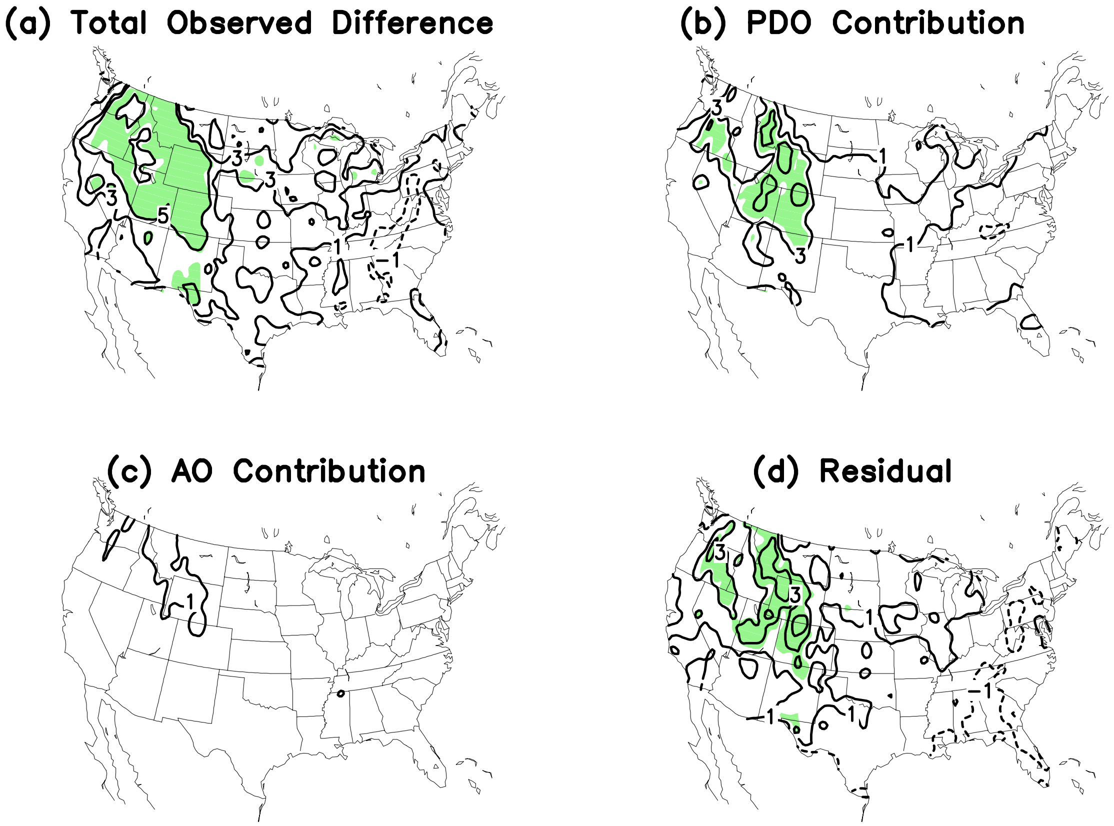
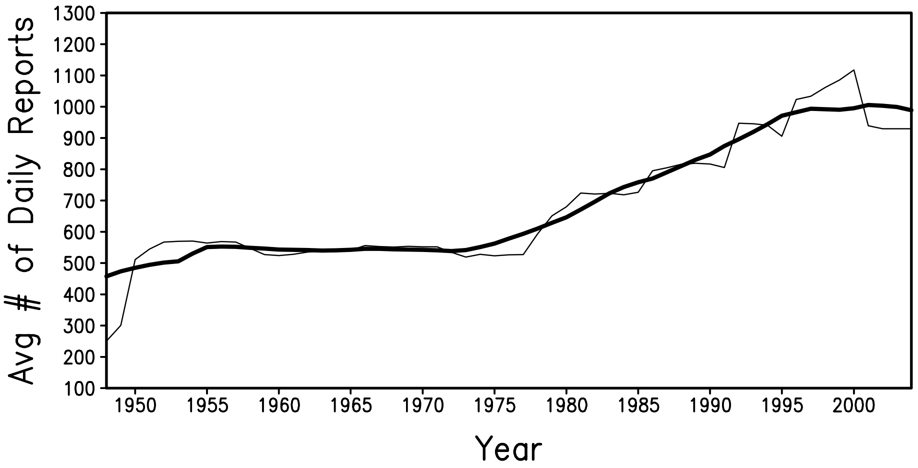


Figure 9 Percent change of the mean frequency of measurable (> 1 mm) daily precipitation occurrence between the period (1976-2004) and the period (1948-1975). Results are expressed as a fraction of the number of days in a year (units: percent). The contours are -5%, -3%, -1%, 1%, 3% and 5%. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.


(a) Station Counts for N. Rockies (115W−105W, 40N−48N)

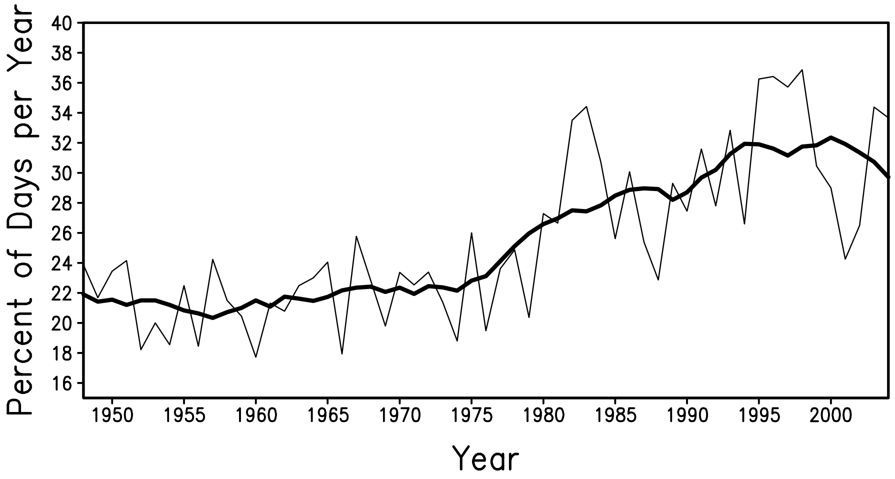

(b) Annual Frequency of Daily Precip (>1 mm) for N. Rockies (Units:%)

Figure 10. (a) Time series of the annual average number of daily station reports for the northern Rockies (115W-105W, 40N-48N) during the period 1948-2004 from the Unified Raingauge Database (URD). (b) Time series of the frequency of measurable (>1 mm) daily precipitation occurrence expressed as a percentage of the number of days in a year for the northern Rockies (115W-105W, 40N-48N).

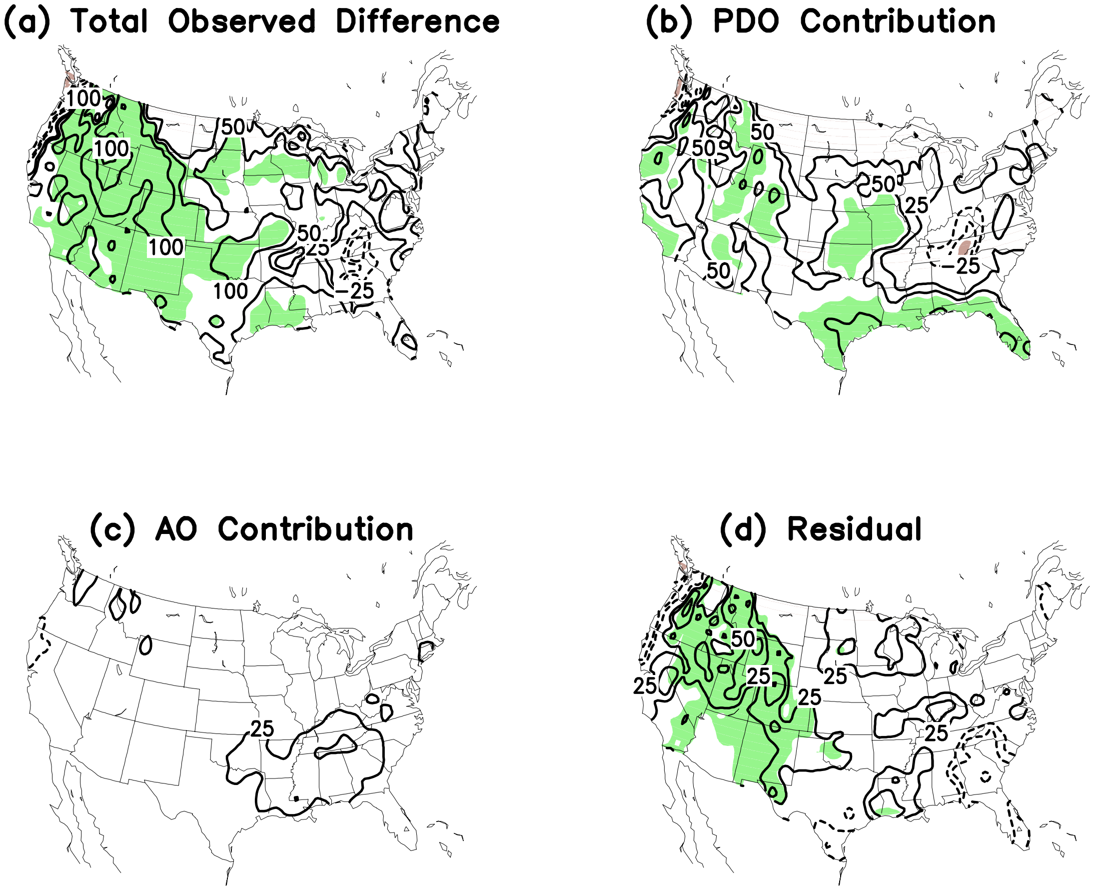


Figure 11. Change of the total accumulated precipitation per year (units: mm/year) due to wet days (> 1 mm) between the period (1976-2004) and the period (1948-1975). The contours are -100 mm, -50 mm, -25mm, 25 mm, 50 mm and 100 mm. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.

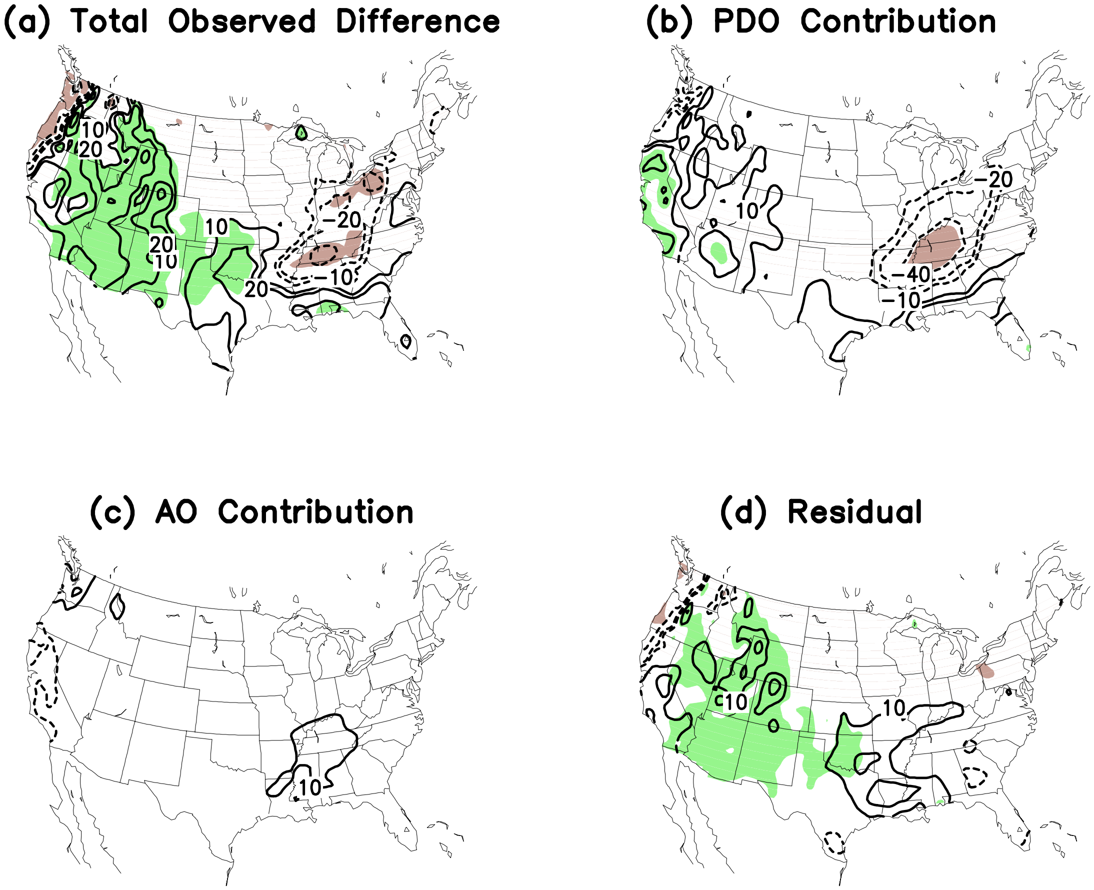
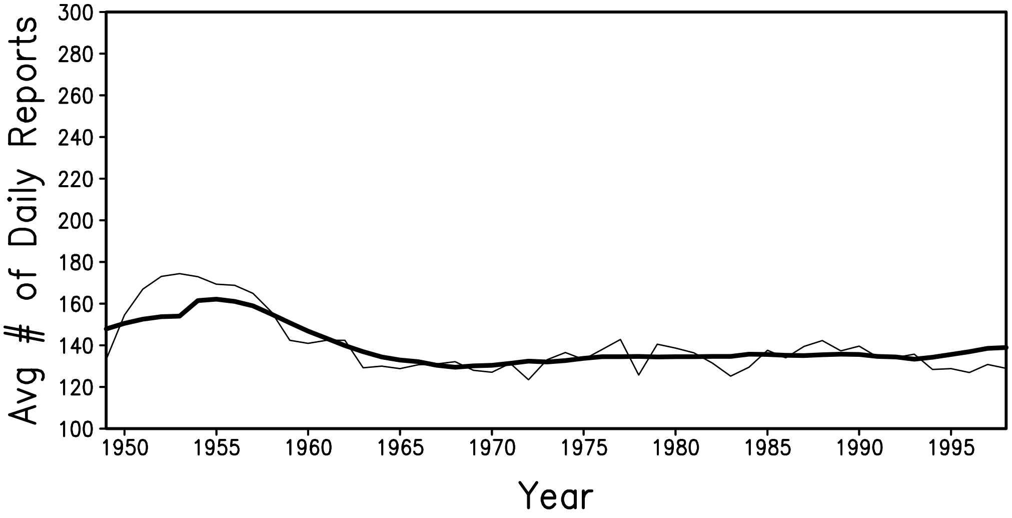


Figure 12. Change of the total accumulated precipitation per year (units: mm/year) due to heavy (> 90th percentile) precipitation days between the period (1976-2004) and the period (1948-1975). The contours are -40 mm, -20 mm, -10 mm, 10 mm, 20 mm and 40 mm. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.

(a) Station Counts for N. Rockies (115W–105W, 40N–48N) – HPD



(b) Annual Frequency of Daily Precip (>1 mm) for N. Rockies (Units:%) – HPD

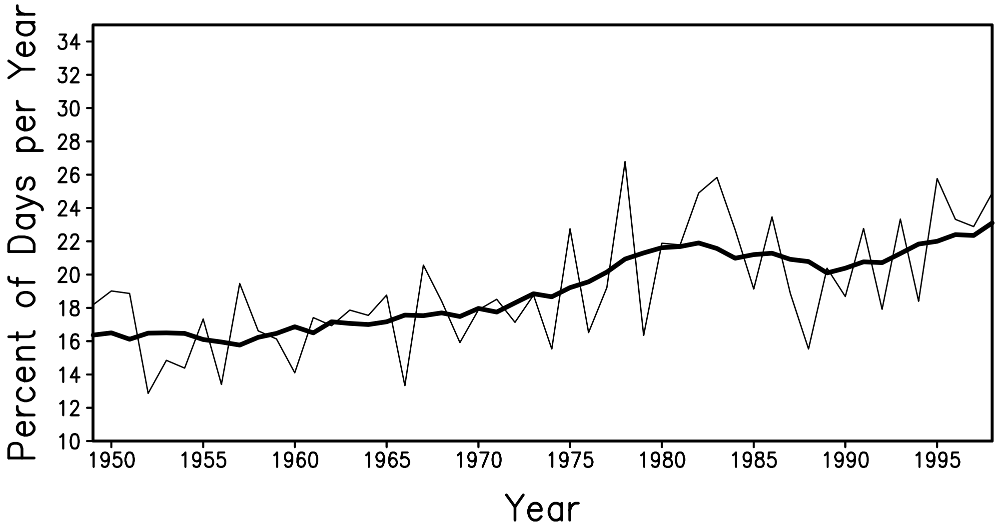


Figure 13. (a) Time series of the annual average number of daily station reports for the northern Rockies (115W-105W, 40N-48N) during the period 1948-1998 from the Hourly Precipitation Database(HPD). (b) Time series of the frequency of measurable (>1 mm) daily precipitation occurrence expressed as a percentage of the number of days in a year for the northern Rockies (115W-105W, 40N-48N) as obtained from the HPD.

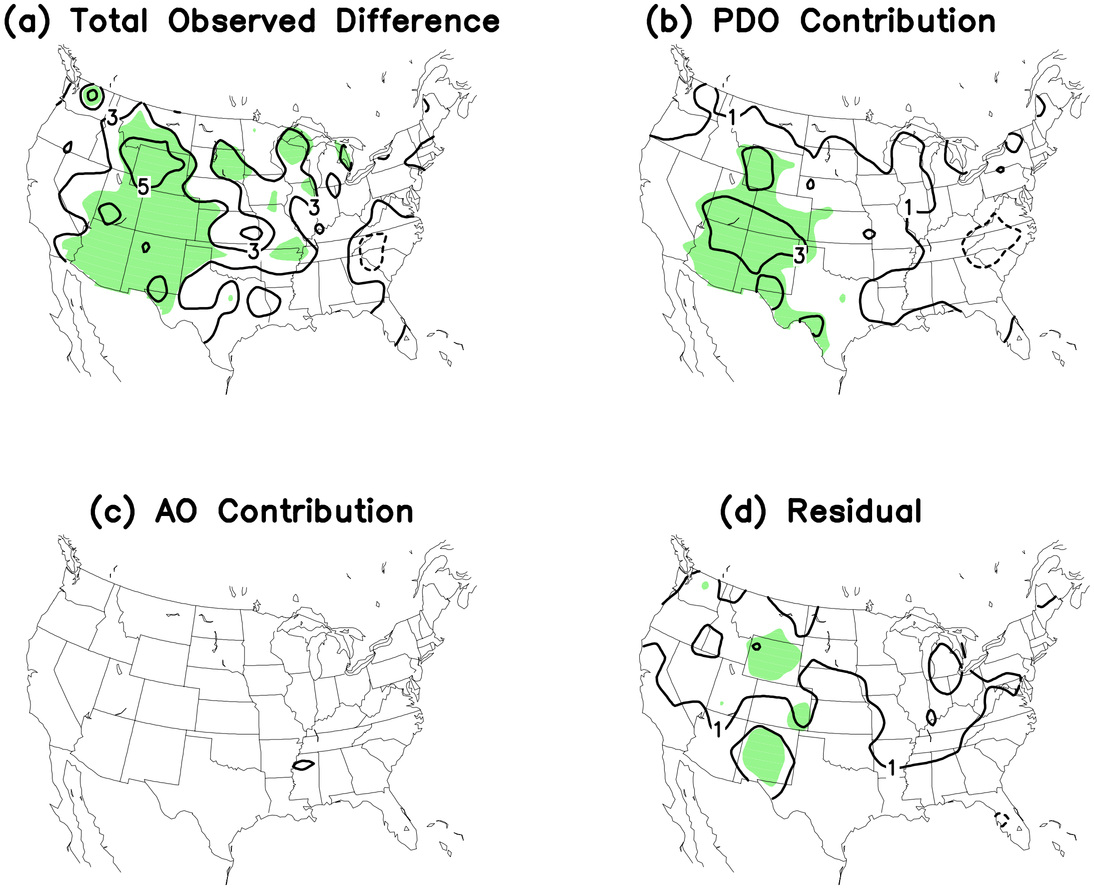


Figure 14. Percent change of the mean frequency of measurable (> 1 mm) daily precipitation occurrence between the period (1976-1998) and the period (1948-1975) from the HPD. Results are expressed as a fraction of the number of days in a year (units: percent). The contours are -5%, -3%, -1%, 1%, 3% and 5%. (a) Total observed change, (b) PDO-related contribution to the observed change, (c) AO-related contribution to the observed change, (d) Residual (total observed change minus PDO-related and AO-related contributions). Shading indicates areas where changes are significant at the 95% level.