Changes in Observed Daily Precipitation over the United States Between 1950-1979 and 1980-2009

By

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Abstract

Changes in observed daily precipitation over the conterminous United States between two 30 year periods (1950-1979 and 1980-2009) are examined using a 60-year daily precipitation analysis obtained from the CPC Unified Raingauge Database. Several simple measures are used to characterize the changes, including mean, frequency, intensity, and return period. Seasonality is accounted for by examining each measure for four non-overlapping seasons. The possible role of the El Niño Southern Oscillation (ENSO) cycle as an explanation for differences between the two periods is also examined.

There have been more light (1 mm $\leq$ P $<$ 10 mm), moderate (10 mm $\leq$ P $<$ 25 mm) and heavy (P $\geq$ 25 mm) daily precipitation events (P) in many regions of the country during the more recent 30-year period, with some of the largest and most spatially coherent increases over the Great Plains and lower Mississippi Valley during autumn and winter. Some regions, such as portions of the Southeast and the Pacific Northwest have seen decreases, especially during the winter. Increases in multi-day heavy precipitation events have been observed in the more recent period, especially over portions of the Great Plains, Great Lakes, and Northeast. These changes are associated with changes in the mean and frequency of daily precipitation during the more recent 30-year period. Difference patterns are strongly related to the ENSO cycle, and are consistent with the stronger El Niño events during the more recent 30-year period. Return periods for both heavy and light daily precipitation events during 1950-1979 are shorter during 1980-2009 at most locations, with some notable regional exceptions.

1.0 Introduction

This study focuses on changes in observed daily precipitation statistics over the conterminous United States during a 60 year period (1950-2009). Emphasis is placed on the differences between two 30-year sub-periods (1950-1979 and 1980-2009). The analysis is carried out using gridded station data for the conterminous United States, where the spatial coverage and temporal continuity of the data are relatively good. Several simple measures are used to characterize changes in daily precipitation between the two 30-year periods, including mean, frequency, intensity, return period, spatial extent and seasonality. Seasonality is accounted for by examining each measure for four non-overlapping seasons (January-March, April-June, July-September and October-December, hereafter JFM, AMJ, JAS, and OND, respectively), using daily data in each case.

Many approaches have been used for estimation and extrapolation of trends in climate time series (e.g. Livezey et al. 2007 discuss four approaches), but the results are often heavily dependent on the endpoints. In this study the emphasis is on changes in the average statistics for two successive 30-year periods (1950-1979 and 1980-2009) in order to minimize the effects of the choice of endpoint on the results. This approach is used to avoid fitting trend lines which are sensitive to the choice of endpoints. Because the focus is on changes in average statistics between the two 30 year periods, the results are unlikely to be very sensitive to small shifts in the specific years that define each period (e.g. shifts of a year or two), though this is not explicitly tested. However, issues related to the choice of change points and whether similar statistics are obtained using different 30 year periods are not addressed.

Return periods (also referred to as recurrence intervals) are often used as an alternative to estimate intervals of time between climate events. There are various methods to calculate them, and quite often the periods for extreme events are much longer than the length of the historical record (e.g. 500 years). The robustness of return period estimates increases for lighter events away from the tails of the distribution. As an example of a traditional application, Wehner (2005) used IPCC AR4 climate model projections to show how currently rare extremes (1-in-20-year events) are projected to become more commonplace by the end of this century. Climate model projections such as these often show more coherent patterns than those in the observations, often due (at least in part) to the decreased variability in the climate models compared to observations.

Increases in heavy precipitation events have been documented in many regions around the world for at least the last 60 years (e.g. IPCC 2011) and in some cases for the 20th century (Kunkel et al. 2003, 2008; Groisman et al. 2005, 2012). Notably, Groisman et al (2012) documented significant increases in the frequency of ‘‘very heavy’’ rain events (defined as daily events above 3 inches) and “extreme” precipitation events (defined as daily and multi-day rain events with totals above 6 inches) over the central United States during a recent 31-year period (1979-2009) when compared to the previous 31-year period (1948-1978). The present study builds on the work of Groisman et al (2012) to consider changes in the frequency and intensity of all daily and multi-day precipitation events over the United States.

In this study return periods are also used to estimate intervals of time between daily precipitation events in the two 30-year periods. The analysis is restricted to return periods that are no longer than one-third the length of a sub-period (i.e. 10 years), and intervals for both heavy events and light events (away from the tail of the daily precipitation distribution) are considered.

In other studies Probable Maximum Precipitation (PMP), defined as *"the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of the year"* (WMO, 1986) has been used. For example, the possible effects of climate change on return periods and PMP were investigated in Kunkel et al. (2012). The study involved improved understanding of linkages between the radiative energy balance, ocean heat storage, sea surface temperatures, and atmospheric water vapor content. The extent to which increases in atmospheric water vapor content tied to increases in greenhouse gas concentrations may have led to changes in daily precipitation over the conterminous United States during the past several decades is not examined here.

Our study builds on previous work on daily precipitation statistics over the United States (e.g. Higgins et al. 2008) which uncovered significant biases in the observations due to inhomogeneities in station coverage (particularly in the western United States) and inadequate quality control of the station observations. The present study benefits from recent work at the Climate Prediction Center (CPC) to develop an observed daily precipitation analysis for the period (1950-present) from the CPC Unified Raingauge Database (Higgins et al. 2008; Higgins et al. 2000), including a state-of-the-art quality control system and Optimal Interpolation (OI) analysis scheme (Chen et al. 2008).

All gridded analyses have inherent limitations, so it is important to carefully document these before drawing conclusions. Higgins et al. (2010) examined time series of the total number of stations used in a gridded analysis (Optimal Interpolation) for the conterminous United States, which included a substantial increase in station counts in the early 1990’s (particularly in the western United States) due to the addition of the SNOwpack TELemetry (SNOTEL) real-time data from the National Resources Conservation Service (http://www.wcc.nrcs.usda.gov/snow/)

and the Hydrometeorological Automated Data System (HADS) real-time data from the National Weather Service Office of Hydrologic Development (see http://www.nws.noaa.gov/ohd/hads/). In this study the effects of changes in station data in the western United States during 1980-2009 on changes in daily precipitation between the two 30-year periods are considered by comparing area means for the conterminous United States to area means for the eastern United States (i.e. area means in which the western United States is excluded).

Many studies have examined relationships between daily precipitation and climate variability, including ENSO (e.g. Gershunov and Barnett 1998; Gershunov and Cayan 2003; Groisman et al. 1999; Higgins et al. 2007; Karl and Knight 1998; Kiladis and Diaz 1989; Mo and Higgins 1998; Ropelewski and Halpert 1986, 1996; Trenberth et al. 2003). When these studies are considered together, it is fair to conclude that there is not a consensus on the local and regional impacts of interannual climate variability on daily precipitation over the United States. There are many reasons for this, including the relatively low-resolution of the datasets employed in many of the earlier studies and the limited number of realizations of the leading patterns of climate variability (e.g. ENSO) in the historical record. The high resolution daily precipitation analysis used here (horizontal resolution is roughly 25 km) offers an opportunity to re-examine these linkages in more detail than was possible in many of the earlier studies.

In this study the focus is on the extent to which changes in daily precipitation between the two 30-year periods are associated with changes in the intensity of the ENSO events between the periods. The ENSO analysis is based on NOAA's Oceanic Niño Index (ONI) that measures the sea surface temperature (SST) anomalies for the Niño 3.4 region. An implicit assumption in this choice is that the ENSO patterns did not change substantially between the two periods, except for their intensity. In fact, ENSO variability may manifest in different structures between the two periods, but this is not accounted for in the present analysis. In addition, the extent to which any changes are forced by factors such as greenhouse gases, land use – land cover changes, and aerosols is not examined.

In the future, results from this study will be used to investigate daily precipitation statistics in the operational NCEP Climate Forecast System (CFS) version 2, with the purpose of identifying and correcting model biases within a season to improve the CPC operational climate forecast products. The investigation will necessarily include bias correction of the CFS version 2 reanalysis data (Saha et al. 2010) and CFS Version 2 reforecasts (Saha et al. 2012).

A brief summary of the data sets and methodology (section 2) is followed by the examination of changes in daily and multi-day precipitation events between the two 30-year periods (section 3). A discussion of the results and some considerations for future studies follows (section 4).

2.0 Data Sets and Methodology

2.1 Observed Precipitation

The observed daily precipitation analysis was obtained from the CPC Unified Raingauge Database (Dr. Pingping Xie, personal communication, 2011; Higgins et al. 2008; Higgins et al. 2000). The database averages roughly 17000 daily station reports around the globe, with excellent coverage over the United States (roughly 8000 daily station reports). The database was used to produce a multi-year (1950-present) daily precipitation analysis (12Z-12Z) for the conterminous United States. The daily data were gridded at a horizontal resolution of (lat, lon) = (0.25°, 0.25°) using an Optimal Interpolation scheme. Several types of quality control (QC) were applied including a "duplicate station” check, a “buddy” check, a “standard deviation” check (which compares the daily data against a gridded daily climatology), and when possible - a radar QC step (in which station reports with erroneous zero values are detected), and a satellite QC step (in which satellite based estimates of precipitation are used to screen erroneously heavy hourly radar precipitation estimates). Previous assessments of objective techniques for gauge-based analyses of global daily precipitation (e.g. Chen et al. 2008) have shown that Optimal Interpolation-based schemes are among the best over the complex terrain of the western United States, though we acknowledge that our particular choice of analysis scheme is a source of uncertainty.

Gauge-based precipitation analyses have other inherent uncertainties that are related to the gauge network density and to gauge network changes over time. Higgins et al (2010) documented variations in the station coverage for the Optimal Interpolation analysis applied in this study. An examination of the distribution of the average number of stations per grid box for the two periods 1950-1979 and 1980-2006 (Fig. 1, top panels) and the difference (1980-2006 minus 1950-1979) (Fig. 1, bottom panel) shows increases in station density in the western United States as well as many parts of the eastern United States in the more recent period. Much of the increase in station count in the more recent period in the western United States is due to the addition of SNOTEL data while increases in the eastern United States are largely due to the addition of HADS data (see official SNOTEL and HADS websites mentioned earlier). The station archive used to produce Fig. 1 only extends to 2006 despite the fact that the analysis extends to 2010 (Pingping Xie, personal communication, 2012). Figure 1 shows that the station coverage is much greater in the eastern United States than in the western United States throughout the record. For this reason, caution will be applied especially when interpreting results for the western United States, and in particular results for the conterminous United States are compared to results for the eastern United States in area mean plots (Figs. 6 and Figs 11-13).

2.2 El Nino Southern Oscillation (ENSO)

A classification of historical warm (El Niño) and cold (La Niña) episodes developed by the CPC is used to identify changes in interannual variations in daily precipitation over the United States between the two 30-year periods. El Niño and La Niña episodes were identified using the Oceanic Niño Index or ONI (Kousky and Higgins 2007). The ONI was computed from three-month running-mean values of Sea Surface Temperature (SST) departures from average in the Niño 3.4 region using a set of homogeneous historical SST analyses (Extended Reconstructed SST – ERSST version 3 of Smith et al. 2008). The ONI can be found on the Climate Prediction Center website http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.

The NOAA operational definitions of El Niño and La Niña conditions based on the ONI (single three-month season value) are as follows:

El Niño:	ONI ≥ 0.5
La Niña:	ONI ≤ -0.5
ENSO-neutral:	$-0.5 < \text{ONI} < 0.5$

The number of El Niño, La Niña and neutral events in each 30-year period are shown in Table 1. Results are shown for non-overlapping 3-month seasons. In section 3.4 the changes in daily precipitation are linked to changes in the intensity of El Niño and La Niña events during the two 30-year periods. The average intensity of the events, again based on the ONI, is shown in Table 2. Again the results are shown for non-overlapping 3-month seasons. Based on the ONI, the average El Niño event during 1980-2009 is stronger than the average El Niño event during 1950-

1979 in OND, JFM and AMJ. The average La Niña event during 1980-2009 is weaker than the average La Niña event during 1950-1979 throughout the annual cycle, especially in JFM and AMJ.

2.3 Methodology

The daily precipitation data (section 2.1) were ranked at each grid point and for each season (JFM, AMJ, JAS, OND) for each 30-year period. The percent change (1980-2009 minus 1950-1979) was computed for 1) average daily precipitation, 2) the number of daily precipitation events exceeding selected thresholds, and 3) the number of events in selected precipitation intensity bands. The number of daily precipitation events for successive 1 mm precipitation bands are obtained by subtracting the number of events exceeding adjacent thresholds. For example, the counts for the precipitation band 1 mm $\leq$ P < 2 mm is obtained by subtracting the count for P $\geq$ 1mm from the count for P $\geq$ 2 mm, etc.

Changes in the annual number of daily precipitation events between the two 30-year periods (Fig. 5) are examined by first defining light (1 mm $\leq$ P < 10 mm), moderate (10 mm $\leq$ P < 25 mm) and heavy (P $\geq$ 25 mm) precipitation bands. It is important to note that defining these bands is somewhat qualitative and depends on the frequency of daily precipitation which is region specific. Stratification by ENSO phase is based on the ONI (section 2.2). In order to account for seasonality, yet minimize the number of multi-panel plots in the manuscript, spatial maps are shown for four non-overlapping seasons (JFM, AMJ, JAS, OND), referred to as winter, spring, summer and autumn respectively.

For the results in section 3 (Figs. 2-5, and 7-10), locations where daily precipitation is less than 0.5 mm day^{-1} (based on a climatology for 1950-1979) are masked to avoid large differences over areas (such as portions of the West during winter) where the spatial variability is large and average daily precipitation is small. In Fig. 5 we introduce two additional thresholds (1.0 mm day^{-1} and 1.5 mm day^{-1}) for moderate and heavy precipitation bands.

Statistical significance is assessed at the 90% level for changes in average precipitation, changes in the number of daily precipitation events, and changes in the number of multi-day precipitation events (Fig. 2-5 and 7) using the Monte Carlo technique. Differences were computed for 1000 random sample 30-yr periods. Statistical significance for the ENSO results (Figs. 9-10) was not assessed due to the different number of events in the two periods. However, the patterns in the difference maps by ENSO phase have many of the characteristics of those for the straight differences (Figs. 2 and 3) which were subjected to a significance test. All spatial plots in section 3 have been lightly smoothed using a 9-point smoother (GrADS smth9 function).

3.0 Results

3.1 Changes in Daily Precipitation Events

The percent change in average daily precipitation between the two 30-year periods (1980-2009 minus 1950-1979) by season is shown in Fig. 2. Significant increases are evident in many areas of the country, with some of the largest and most spatially coherent increases over the Great Plains and lower Mississippi Valley during JFM and OND. Significant decreases are also evident, particularly over portions of the Southeast and along the Pacific Northwest Coast during JFM. As we will show later, the patterns in Fig. 2 are consistent with changes in the average intensity of ENSO between the two 30-year periods. That is, there have been stronger El Nino’s and weaker La Nina’s, on average, during the more recent 30-year period, especially during the fall and winter seasons.

The percent change in annual precipitation (Fig. 4, top) captures the coherent areas of increase in the central United States and decrease in the Tennessee Valley and along the Pacific Northwest Coast that are evident in the seasonal results (Fig. 2). The results also reflect the fact that in some areas the changes are opposite for different seasons and that the annual values are not just a simple addition of the four panels in Fig. 2.

The percent change in the number of daily precipitation events ($P \geq 1$mm) between the two 30-year periods (Fig. 3) also shows that there have been significant increases in daily precipitation frequency at many locations in the United States throughout the annual cycle, with some notable exceptions again centered on the Tennessee Valley in JFM and in the lower Mississippi Valley in JAS. The changes in the number of daily precipitation events for other selected thresholds (e.g. 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm) were also examined (not shown). Overall, the spatial patterns were quite similar to those shown in Fig. 2, except in areas of the country where the counts for the heavier precipitation thresholds are small or zero (e.g. the Desert Southwest and portions of the Intermountain West). The percent change in the annual number of daily precipitation events (Fig. 4, bottom) reveals a pattern similar to that for the percent change in the annual average daily precipitation (Fig. 4, top), except that the areas experiencing decreases are less evident, especially along the Pacific Northwest Coast.

The percent change in the annual number of daily precipitation events between the two 30-year periods for light ($1 \text{ mm} \leq P < 10 \text{ mm}$), moderate ($10 \text{ mm} \leq P < 25 \text{ mm}$) and heavy ($P \geq 25$ mm) precipitation bands is shown in Fig. 5. Locations where the climatology is less than 0.5 mm day^{-1}, 1.0 mm day^{-1} and 1.5 mm day^{-1} (based on a climatology for the period 1950-1979) are masked for the light, moderate and heavy precipitation bands, respectively. These thresholds are used to avoid large differences over areas (such as portions of the interior West during the winter) where the spatial variability is large and the average daily precipitation is small.

In general, the number of daily precipitation events has increased in all 3 bands, except in portions of the Southeast and in scattered areas of the West for the moderate band (Fig. 5, middle) and in portions of the Southeast and along the Pacific Northwest Coast for the heaviest band (Fig. 5, bottom). Changes in the seasonal number of daily precipitation events for the same bands (not shown) reveal that the decreases in the Southeast for moderate and heavy events are largest during JFM and smallest during OND, while the decreases in areas of the western United States have been observed fairly consistently throughout the annual cycle. Some of the increases in the lightest band in the vicinity of Wyoming may be due to inhomogeneities in the station distribution between the two 30-year periods (e.g. Higgins et al 2008) though this is not explicitly investigated here.

Groisman et al (2012) defined and compared moderate precipitation events ($12.7 \text{ mm} \leq P \leq 25.4 \text{ mm}$) to heavy precipitation events ($P > 25.4$ mm or 1 in), very heavy precipitation events ($P>76.2$ mm or 3 in) and extreme precipitation events ($P>154.9$ mm or 6 in) over the central United States between two 31-year periods (1948-1978 and 1979-2009). They found a statistically significant redistribution in the spectra of daily precipitation frequency in which the moderate precipitation events became less frequent compared to the heavy, very heavy and extreme precipitation events. In the present study we find increases in daily precipitation frequency for light, moderate and heavy precipitation events in this region (Fig. 5), with the caveat that our definitions are somewhat different from those in Groisman et al. (2012). It is important to note that these differences may also be due to differences in methodology. For example, the results in Groisman et al (2012) are based on station data that have been corrected to account for changes in measurement techniques whereas the results here are based on a gridded analysis with quality control (section 2.1). A more thorough examination of changes in the spectra of daily precipitation frequency by season follows.

Distributions of the percent change in the number of daily precipitation events versus daily precipitation amount for the conterminous United States and for the eastern United States were examined. Results were obtained by first determining the number of daily precipitation events for successive 1 mm precipitation intervals at each grid point as described in section 2.3. The distributions shown in Fig. 6 were obtained by taking differences in the counts (1980-2009 minus 1950-1979) at each grid point and then by computing area averages for the conterminous United States (130° W – 65° W; 25° N – 50° N) and the eastern United States (100° W – 65° W; 25° N – 50° N).

In general there have been increases in the number of daily precipitation events in the more recent period throughout the annual cycle over the conterminous United States (Fig. 6, left column), except for moderate rain events during JFM. Increases in the number of events are relatively large for the lightest rain events throughout the annual cycle and for events of all precipitation intensities during OND. Changes were also examined for the eastern United States (Fig. 6, right column) to separate out the possible influences of the introduction of the HADS and SNOTEL data in the western United States during the more recent period. Interestingly, both sets of figures are quite similar, except during JFM when small decreases in the daily precipitation counts for the eastern United States are shifted towards lighter rain events relative to the conterminous United States. This comparison suggests that the HADS and SNOTEL data are not having a significant influence on the qualitative nature of the results.

3.2 Changes in Multi-day Precipitation Events

An examination of the percent change (1980-2009 minus 1950-1979) of the annual number of multi-day events (constructed from daily precipitation events that are two or more consecutive days in duration) for various precipitation thresholds shows that there have been increases in the number of multi-day events at many locations at all precipitation thresholds except over significant portions of the Tennessee Valley and mid-Atlantic where there are decreases at all thresholds (Fig. 7). For clarity, we note that all multi-day events that satisfy the threshold indicated are included in the results. The spatial extent of areas with percent changes significant at the 90% level is greatest for the lighter amounts and less for the heavier amounts. Areas shaded in white (particularly apparent at higher precipitation thresholds in the intermountain west) indicate locations where no multi-day events occurred at the threshold indicated. Substantial increases (exceeding 75% or more) in multi-day heavy precipitation events ($P \geq 25$ mm) have been observed in the more recent period, especially over portions of the Great Plains and Great Lakes regions. An examination of the percent change of the number of 2, 3, 4 and 5 day events (plotted separately and without double counting; not shown) reveal that the patterns, especially at the higher thresholds on Fig. 7, are dominated by changes in the number of 2 day precipitation events.

3.3 Return Periods

Return periods are used to examine how the frequency of rare events may have changed between the two 30-year periods (i.e. 1950-1979 and 1980-2009). The specific issue under consideration is whether rare events, such as daily precipitation events that occurred once every 10 years during 1950-1979, occurred more or less frequently during the 1980-2009 period.

Daily precipitation values (mm) are ranked at each grid point for each month for the two 30-year periods. The method used to calculate return periods is straight forward and easily applied to the ranked daily precipitation data. In particular, 1950-1979 is used as the reference period. The analysis is restricted to return periods that are no longer than one-third the length of a sub-period, and results for 10-yr, 5-yr and 3-yr return periods are explicitly shown. Return periods of 10-, 5-, and 3-years correspond to ranks 3, 6, and 10 in the daily precipitation distribution. For a return period of interest during 1950-1979 (e.g. 10 years), the corresponding ranked daily precipitation amounts at each grid point are used to determine the return periods (RP) during 1980-2009 as follows:

$$RP = (n+1)/m$$

where n is the sample length in years and m is the ranking of the precipitation amount during the 1980-2009 period. The final results below have been smoothed slightly using a 9 point smoother (GrADS smth9 function) without any change in the interpretation of the results.

Maps of the return periods (years) during 1980-2009 for 10- year, 5-year and 3-year daily precipitation events during 1950-1979 are shown in Fig. 8. Results are shown by season after combining the monthly results. Shorter return periods are evident at many locations (e.g. in the central and southern Plains during JFM, but there are nearby regions where the return periods are longer during 1980-2009. In general the patterns are similar for 10-year, 5-year and 3-year return periods.

A simple illustration clarifies why the patterns are similar for different return periods Suppose there are two identical distributions of daily precipitation, hereafter D1 and D2, with all ranked values the same *except* that D2 features one additional event that becomes the new top value. Consequently, the D1 rank-1 value becomes the D2 rank-2 value, the D1 rank-2 value becomes the D2 rank-3 value, etc. That is, all values in D2 are shifted by one position in the ranking when compared to D1. The return periods for similar magnitude events are shorter in D2 than they are in D1.

Returning to the results in Fig. 8, for certain regions and at certain times of the year (e.g. the southern Great Plains during JFM) there are more heavy precipitation events during 1980-2009 than during 1950-1979, and consequently the return periods are shorter during 1980-2009. And, for certain regions and at certain times of the year (e.g. the Pacific Northwest during OND, JFM and AMJ) the opposite is true. These distinct spatial variations in the patterns deserve further investigation. For example, are there changes in wind and circulation features between the two periods that can explain these changes?

A decrease in the return period of a 10-year event (i.e. from 10 years in 1950-1979 to 5 years in 1980-2009), represents a change in ranking from rank 3 in 1950-1979 to rank 6 in 1980-2009. That is, only 3 additional events occurred during the 1980-2009 period to achieve the decrease in return period from 10 years to 5 years. In contrast, a decrease in the return period of a 3-year event in 1950-1979 to a 1-year event in 1980-2009 represents a more substantial change in the ranking from rank 10 in 1950-1979 to rank 30 in 1980-2009. That is, 20 additional events occurred during the 1980-2009 period to achieve the decrease in return period from 3 years to 1 year. Consequently, the results are more robust for return period changes that are deeper in the distribution (i.e. away from the most extreme events where a single event can have a substantial impact on the return periods).

3.4 Role of ENSO

The possible role of changes in the El Niño Southern Oscillation (ENSO) cycle as an explanation for changes in daily precipitation between the two 30-year periods is examined next. The ONI (section 2.2) is used as the basis for determining the number of El Niño, La Niña and neutral events and their average intensity during the two 30-year periods (see Tables 1 and 2). As in section 3.1, the analysis is restricted to non-overlapping seasons (JFM, AMJ, JAS, OND) so that the sample size of daily precipitation events is sufficiently large.

The percent change in the average daily precipitation (1980-2009 minus 1950-1979) was computed for El Niño, La Niña and ENSO-neutral periods (Fig. 9) using the classification given in section 2.2. Consistent with the results in Fig. 2, some of the largest increases in average daily precipitation during El Niño and La Niña were over the Great Plains and lower Mississippi Valley during OND and over the Southwest during JFM. Decreases for both El Niño and La Niña were observed over the Tennessee Valley during JFM. Comparisons of the results for El Niño (Fig. 9a), La Niña (Fig. 9b) and the straight difference (Fig. 2) reveal many areas of the country where the changes are in the same sense. For example, the spatial patterns during OND and JFM are generally in the same sense as the anomaly patterns typically associated with El Niño (i.e. wetter-than-normal along the southern tier-of-states and drier-than-normal in the Ohio and Tennessee Valleys), so it is reasonable to conclude that the net changes between the two 30-year periods are largely explained by the increase (decrease) in average intensity of El Niño (La Niña) between the periods. The percent change in the number of daily precipitation events ($P \geq 1$mm) between the two 30-year periods by ENSO phase (Fig. 10) also yields similar patterns to those shown in Fig. 9. Overall, both changes in daily precipitation frequency and intensity are consistent with the increase (decrease) in average intensity of El Niño (La Niña) during the more recent 30-year period (i.e. 1980-2009).

The distribution of changes in the number of daily precipitation events versus intensity by ENSO phase for the conterminous United States (130° W – 65° W; 25° N – 50° N) and eastern United States (100° W – 65° W; 25° N – 50° N) are examined in Figs. 11-13. Increases in the number of light daily precipitation events (1 mm ≤ P < 10 mm) over the conterminous United States are similar throughout the annual cycle for El Niño (Fig. 11), ENSO- neutral (Figs. 13) and for the more recent 30-year period (Fig. 6). Increases in the number of light events over the conterminous United States are similar for La Niña (Fig. 12) during AMJ, JAS and OND, but are smaller with some areas actually showing decreases during JFM.

In the fall (OND) there was a roughly 10% increase in the number of moderate (10 mm ≤ P < 25 mm) and heavy (P ≥ 25 mm) daily precipitation events over the conterminous United States during the most recent 30-year period (Fig. 6). Similar increases have been observed during El Niño (Fig. 11), La Niña (Fig. 12), and ENSO-neutral (Fig. 13) events during the fall. In contrast, during the winter, spring and summer the changes have been much smaller during the most recent 30-year period (Fig. 6). Some of the changes were much larger during El Niño, La Niña and ENSO neutral periods (depending on the season and the intensity of the events), but these large changes were often in the opposite sense to account for the small net changes.

4.0 Summary

There have been more light (1 mm ≤ P < 10 mm), moderate (10 mm ≤ P < 25 mm) and heavy (P ≥ 25 mm) daily precipitation events in many regions of the country during the period 1980-2009 than during the period 1950-1979, although there are notable regional exceptions (e.g. over the Tennessee Valley and along the Pacific Northwest Coast during JFM). The increases in daily (and multi-day) heavy precipitation events are associated with changes in the mean and frequency of occurrence of daily precipitation events during the more recent 30-year period. The difference patterns are strongly related to the ENSO cycle, and are consistent with the stronger El Niño events and weaker La Niña events during the more recent 30-year period. Return periods for both heavy and light daily precipitation events during 1950-1979 are shorter during 1980-2009 at many locations, but again there are notable regional exceptions, especially in the Southeast and over the western United States.

Our confidence in the observed changes in extremes depends on the quality and quantity of data, which is relatively good over the United States, especially the eastern 2/3rd of the country. Extreme events are rare which means there are relatively few data available to make assessments regarding changes in their frequency or intensity. The rarer the event the more difficult it is to identify long-term changes. This is consistent with the results presented here on return periods.

In follow on studies we plan to investigate the ability of the Climate Forecast System (CFS) version 2 reanalysis (which is currently being extended back to 1948) to reproduce the changes in daily precipitation reported in this study. Observed precipitation is not directly assimilated into the CFS version 2 reanalysis, so this will be a good test of the fidelity of the analyzed daily precipitation. We will also build on this work to investigate the ability of the CFS reforecasts to capture the spatial and temporal variability of daily precipitation over the conterminous United States. Comparisons between observations and the reforecasts will reveal the spatial and temporal variability of the bias in daily precipitation as a function of lead and season. Bias correction techniques (e.g. based on the probability distribution function matching) will be employed to correct the bias of the CFS daily precipitation forecasts using the CPC Unified daily gauge analyses. Since the CPC daily precipitation analysis is global, we also intend to look at daily precipitation statistics at other locations outside the conterminous United States where the input data is sufficiently dense. This will include comparisons to the CFS reforecasts and forecasts in these regions.

5.0 Acknowledgments

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7.0 Table Captions

Table 1. The number of El Niño, La Niña and ENSO-neutral events based on the Oceanic Niño Index (ONI) during 1950-1979 (left) and 1980-2009 (right). Results are shown for non-overlapping 3-month seasons.

Table 2. The average value of the Oceanic Niño Index (ONI) for each phase of the ENSO cycle during 1950-1979 (left) and 1980-2009 (right). Results are shown for non-overlapping 3-month seasons.

8.0 Figure Captions

Figure 1. Average number of stations per grid box for the periods 1950-1979 and 1980-2006 (the archive of historical analyses only goes to 2006) (top panels) and for the difference (1980-2006 minus 1950-1979).

Figure 2. Percent change in average daily precipitation (1980-2009 minus 1950-1979). Differences are computed at each grid point and results are shown by season. A nine-point smoother was applied to the data. Locations where the average daily precipitation is less than 0.5 mm day^{-1} (based on climatology for 1950-1979) are masked. Areas enclosed by contours are significant at the 90% confidence level.

Figure 3. Percent change in the number of daily precipitation events (1980-2009 minus 1950-1979) for precipitation greater than or equal to 1 mm. Differences are computed at each grid point and shown by season. A nine-point smoother was applied to the data. Locations where the average daily precipitation is less than 0.5 mm day^{-1} (based on climatology for 1950-1979) are masked. Areas enclosed by contours are significant at the 90% confidence level.

Figure 4. Top: Percent change in annual average daily precipitation (1980-2009 minus 1950-1979). Bottom: Percent change in the number of daily precipitation events (1980-2009 minus 1950-1979) for precipitation greater than or equal to 1 mm. In each case, differences are computed at each grid point. A nine-point smoother was applied to the data. Locations where the average daily precipitation is less than 0.5 mm day^{-1} (based on climatology for 1950-1979) are masked. Areas enclosed by contours are significant at the 90% confidence level.

Figure 5. Percent change in the annual number of daily precipitation events (1980-2009 minus 1950-1979) for light (1 mm $\leq$ P < 10 mm), moderate (10 mm $\leq$ P < 25 mm) and heavy (P $\geq$ 25 mm) daily precipitation bands. Differences are computed at each grid point. A nine-point smoother was applied to the data. Locations where the local climatology is less than 0.5 mm day^{-1}, 1.0 mm day^{-1}, and 1.5 mm day^{-1} (based on climatology for 1950-1979) are masked for the light, moderate, and heavy daily precipitation bands, respectively. Areas enclosed by contours are significant at the 90% confidence level.

Figure 6. Percent change in the number of daily precipitation events (1980-2009 minus 1950-1979) for the conterminous United States (130° W – 65° W; 25° N – 50° N) (left) and for the eastern United States (100° W – 65° W; 25° N – 50° N) (right). Results are shown by season for 1-10 mm and 10-50 mm bands based on computations at 1 mm intervals. The convention for the x-axis labels is as follows: 1, 2, … refer to the intervals 1-2 mm, 2-3 mm, ..., etc.

Figure 7. Percent change in the annual number of multi-day (2 days or greater) daily precipitation events (1980-2009 minus 1950-1979) for daily precipitation amounts at or above various thresholds as indicated. Differences are computed at each grid point and are annual (i.e. based on all seasons). All multi-day events that satisfy the threshold on consecutive days are included. A nine-point smoother was applied to the data. Areas shaded in white (particularly

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Figure 9. Percent change in average daily precipitation (1980-2009 minus 1950-1979) for El Niño, La Niña and ENSO neutral periods. Differences are computed at each grid point and results are shown by season. A nine-point smoother was applied to the data. Locations where the average daily precipitation is less than 0.5 mm day^{-1} (based on climatology for 1950-1979) are masked.

Figure 10. Percent change in the number of daily precipitation events (1980-2009 minus 1950-1979) for precipitation greater than or equal to 1 mm for El Niño, La Niña and ENSO neutral periods. Differences are computed at each grid point and shown by season. A nine-point smoother was applied to the data. Locations where the average daily precipitation is less than 0.5 mm day^{-1} (based on climatology for 1950-1979) are masked.

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Figure 12. Percent change in the number of daily precipitation events (1980-2009 minus 1950-1979) during La Niña for the conterminous United States (130° W – 65° W; 25° N – 50° N) (left) and for the eastern United States (100° W – 65° W; 25° N – 50° N) (right). Results are shown by season for 1-10 mm and 10-50 mm bands based on computations at 1 mm intervals. The convention for x-axis labels is as follows: 1, 2,… refer to intervals 1-2 mm, 2-3 mm,..., etc.

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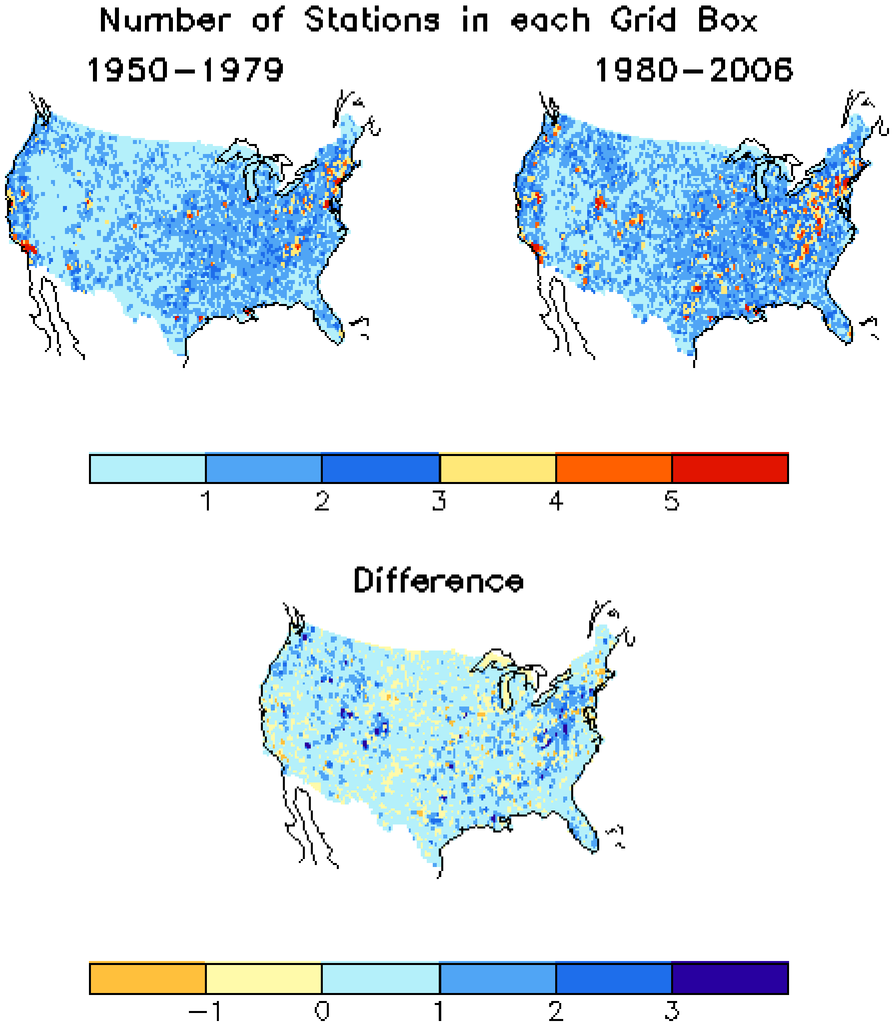
	1950-1979			1980-2009		
	El Niño	**La Niña**	**Neutral**	**El Niño**	**La Niña**	**Neutral**
JFM	6	9	15	8	10	12
AMJ	5	10	15	10	7	13
JAS	5	11	14	11	4	15
OND	10	12	8	11	8	11

Table 1. The number of El Niño, La Niña and ENSO-neutral events based on the Oceanic Niño Index (ONI) during 1950-1979 (left) and 1980-2009 (right). Results are shown for non-overlapping 3-month seasons.

	1950-1979			1980-2009		
	El Niño	**La Niña**	**Neutral**	**El Niño**	**La Niña**	**Neutral**
JFM	0.95	-1.10	0.01	1.20	-0.93	0.12
AMJ	0.58	-0.81	-0.05	0.77	-0.64	0.08
JAS	0.98	-0.89	0.04	0.93	-0.85	-0.05
OND	1.00	-1.15	-0.10	1.38	-1.10	-0.10

Table 2. The average value of the Oceanic Niño Index (ONI) for each phase of the ENSO cycle during 1950-1979 (left) and 1980-2009 (right). Results are shown for non-overlapping 3-month seasons.



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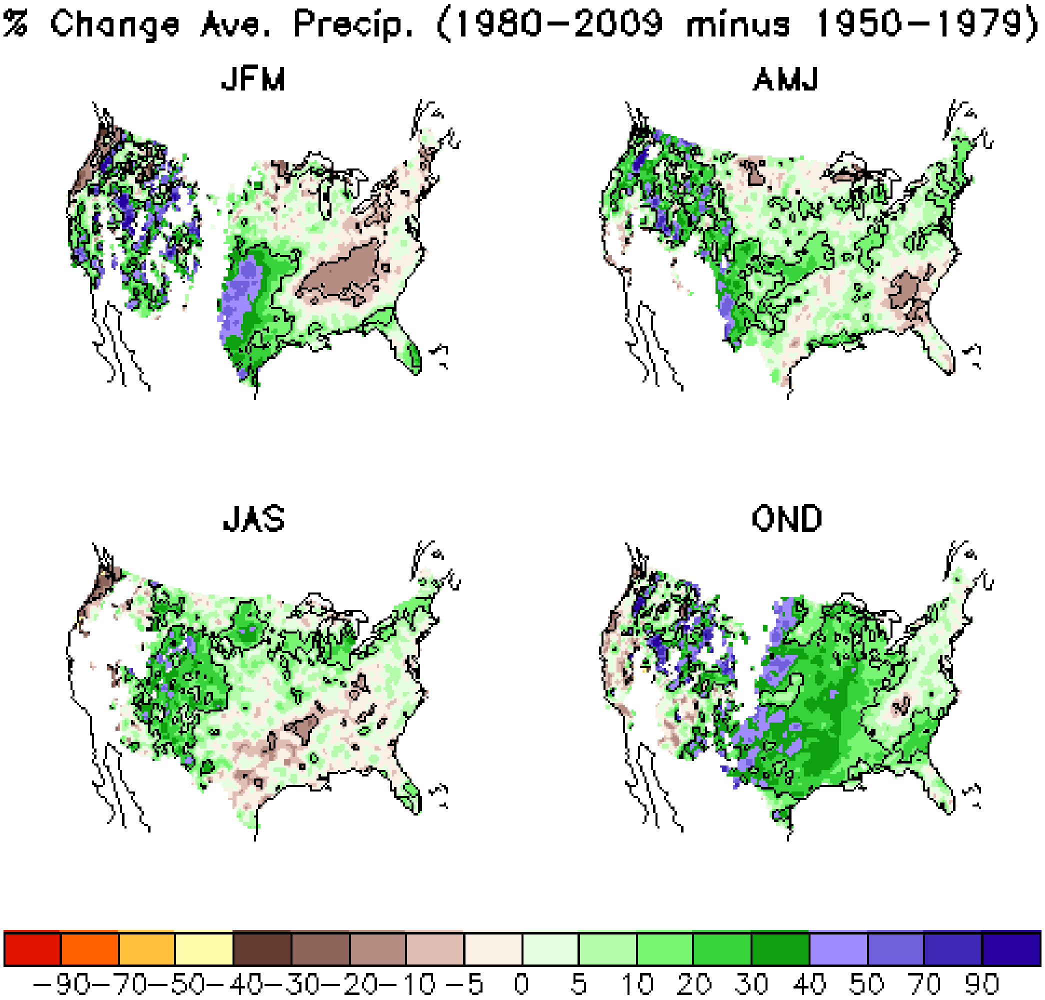

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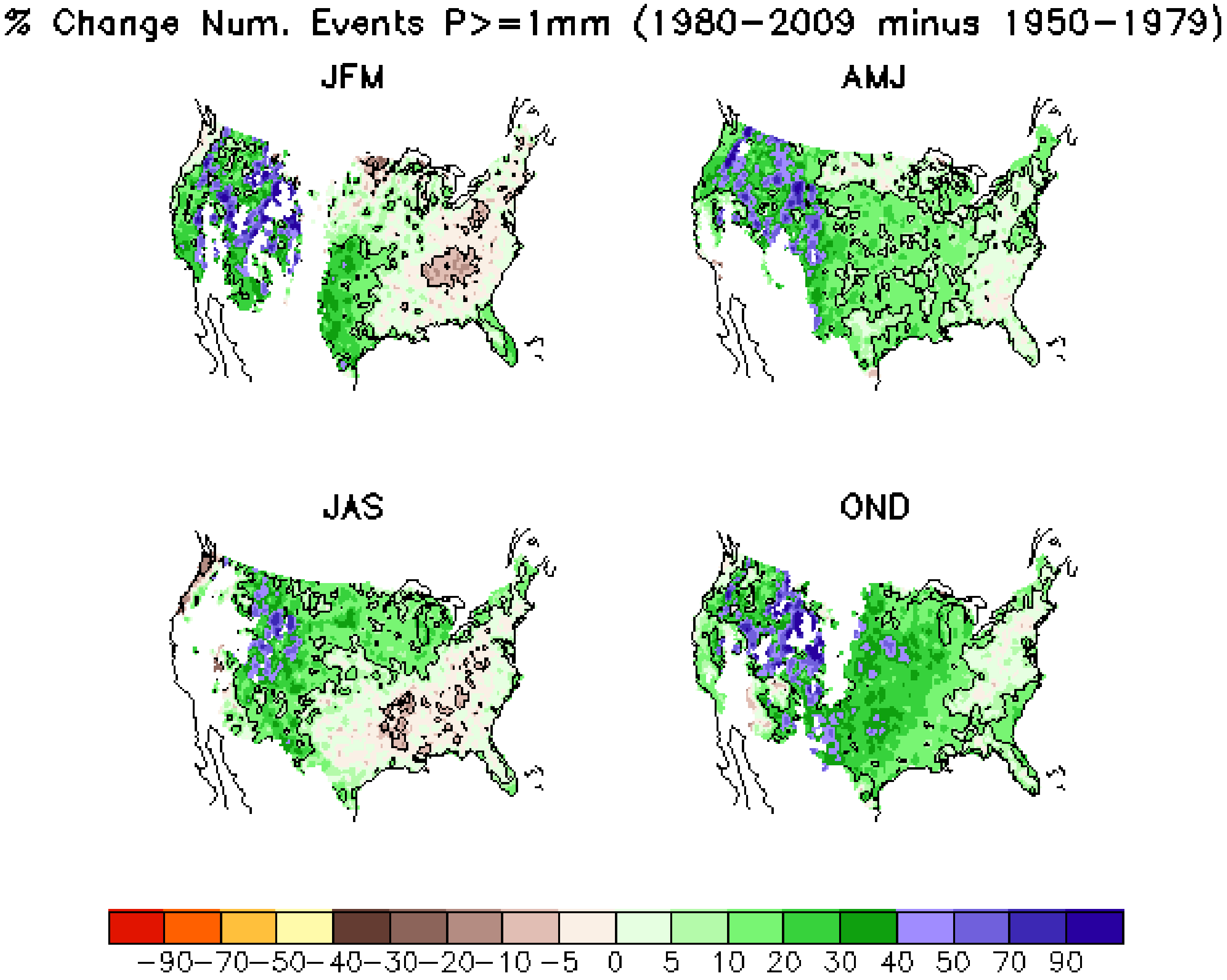

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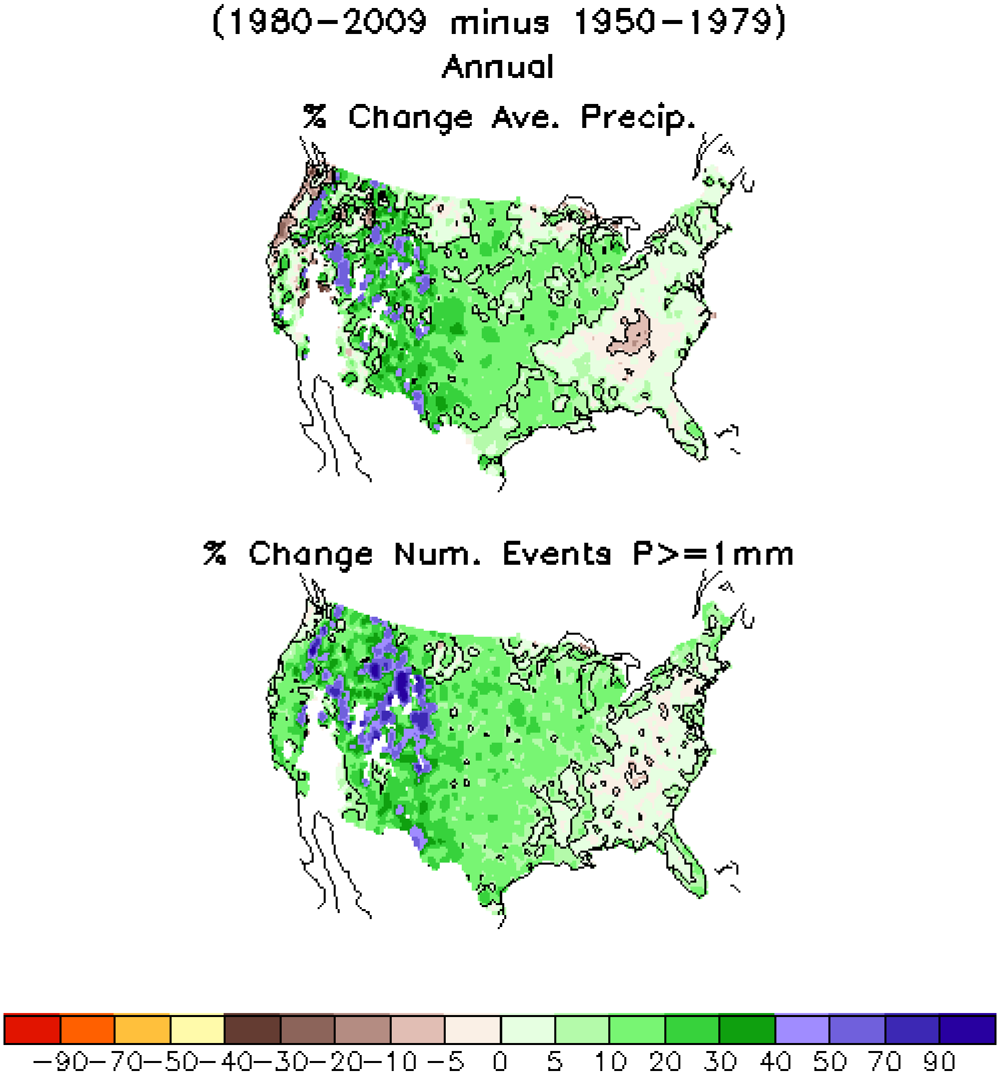

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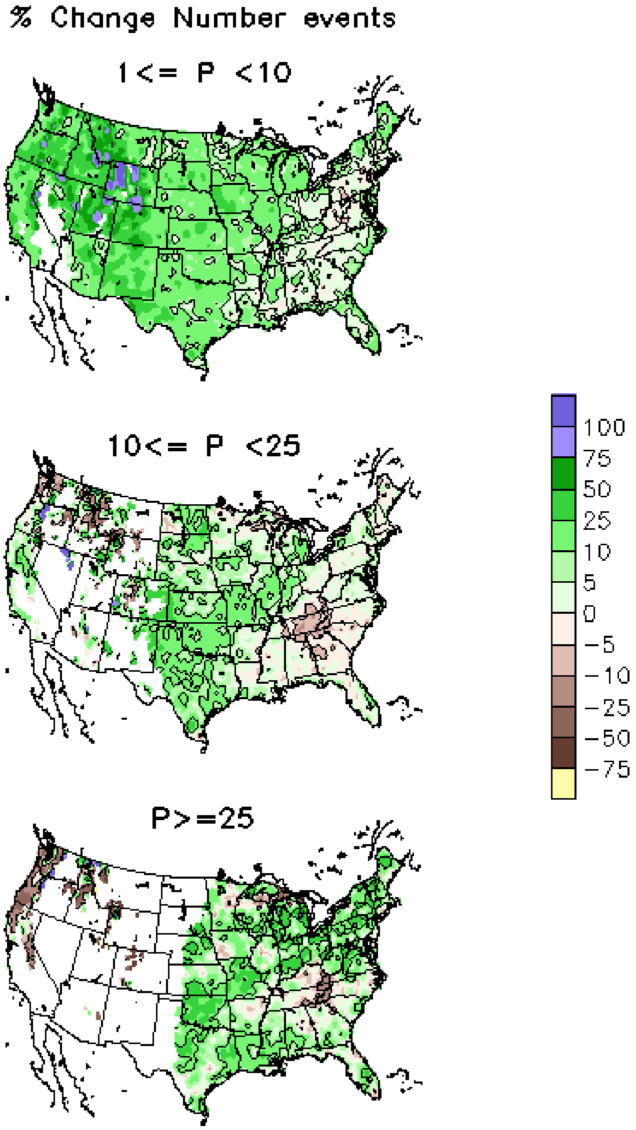

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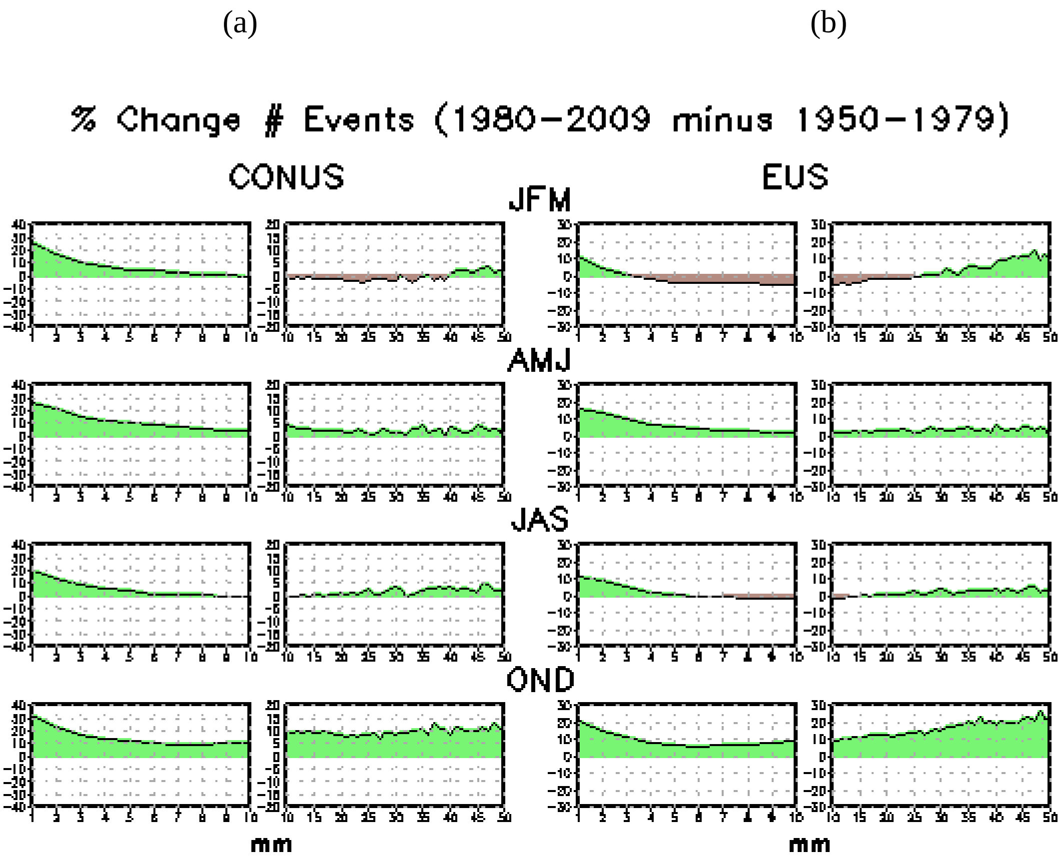

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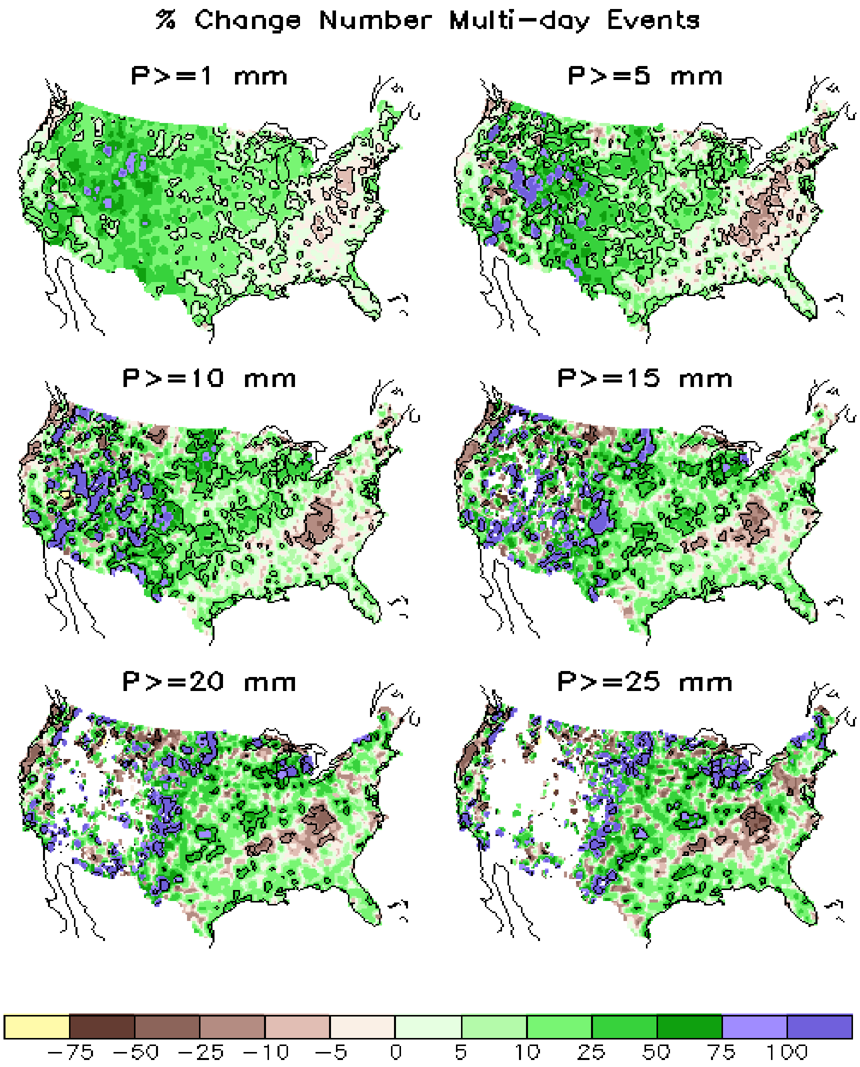

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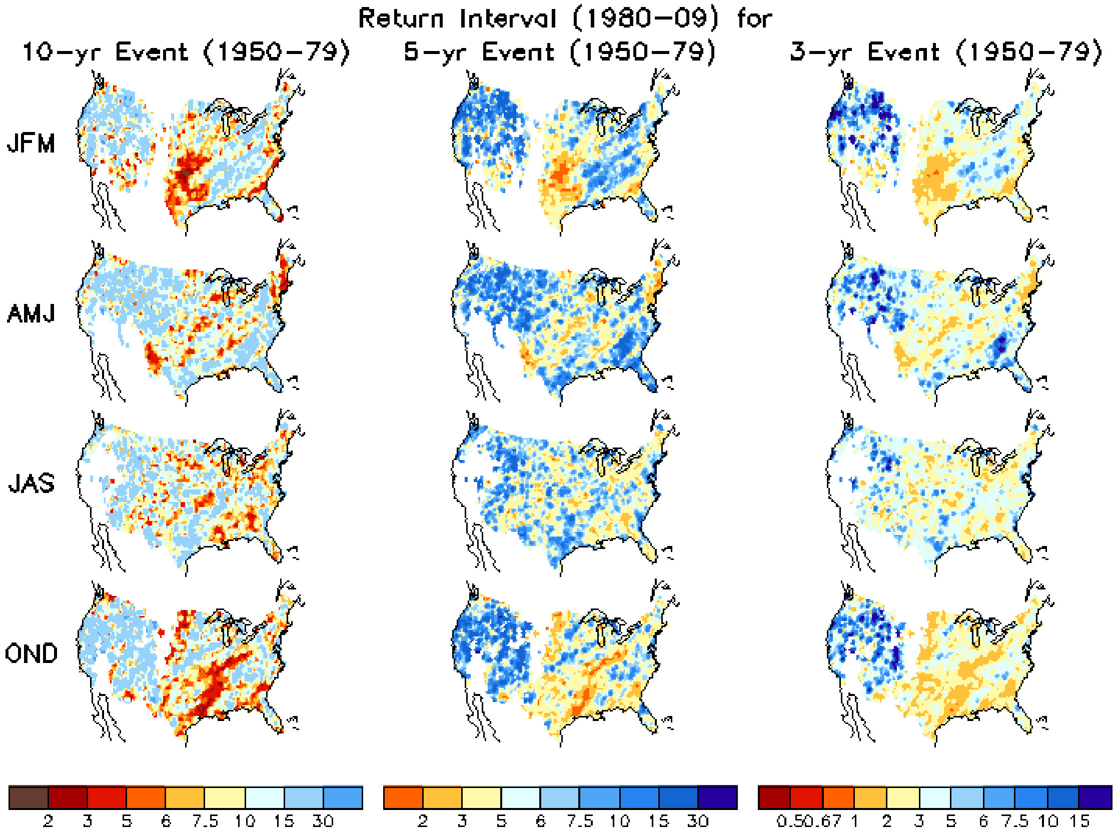

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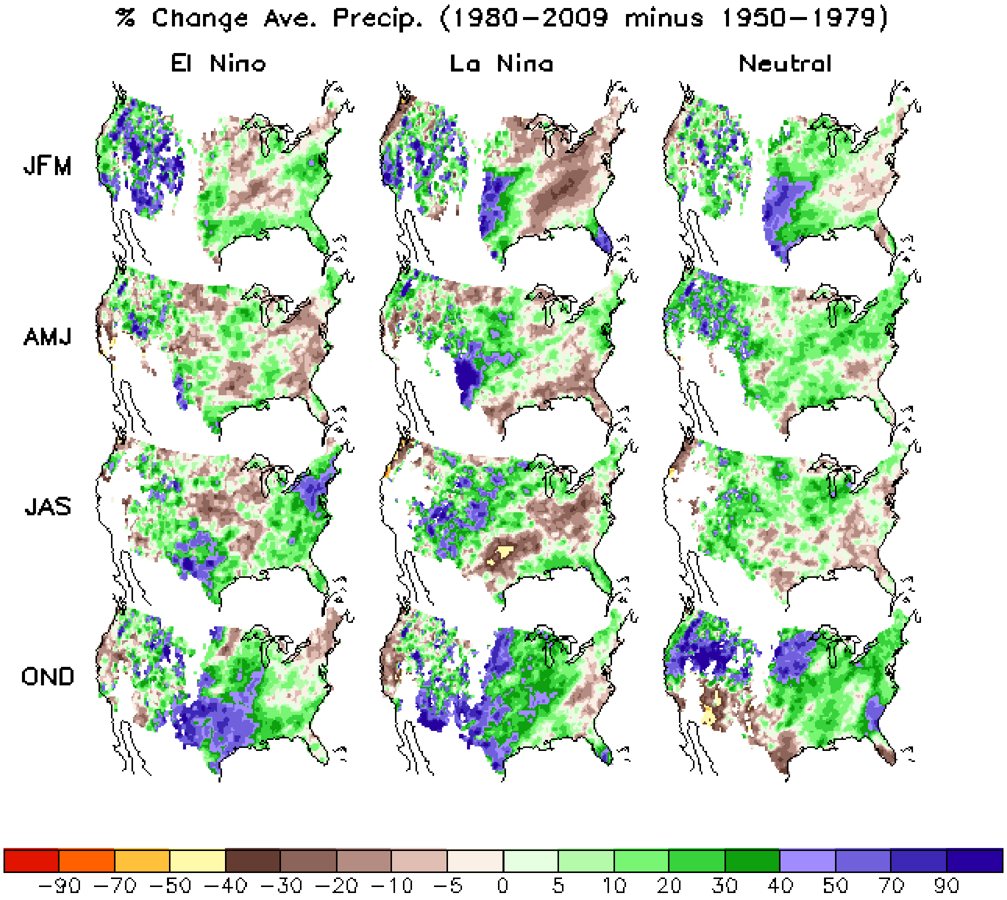

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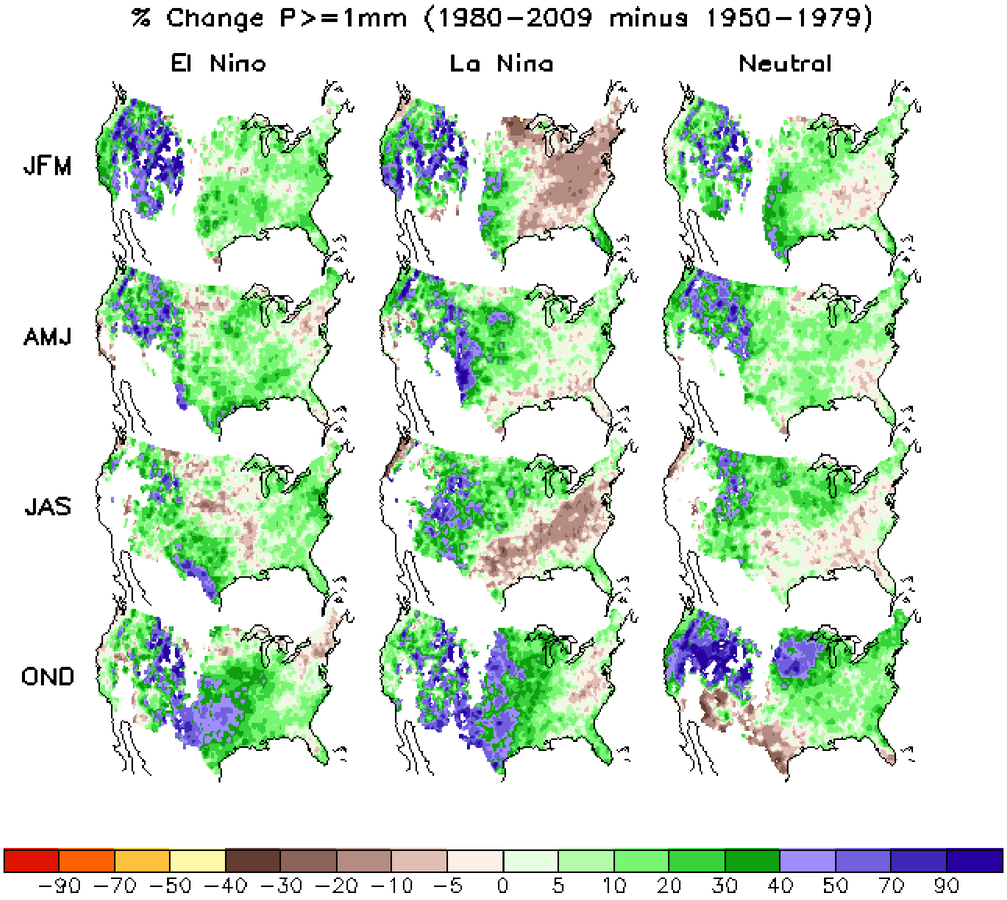

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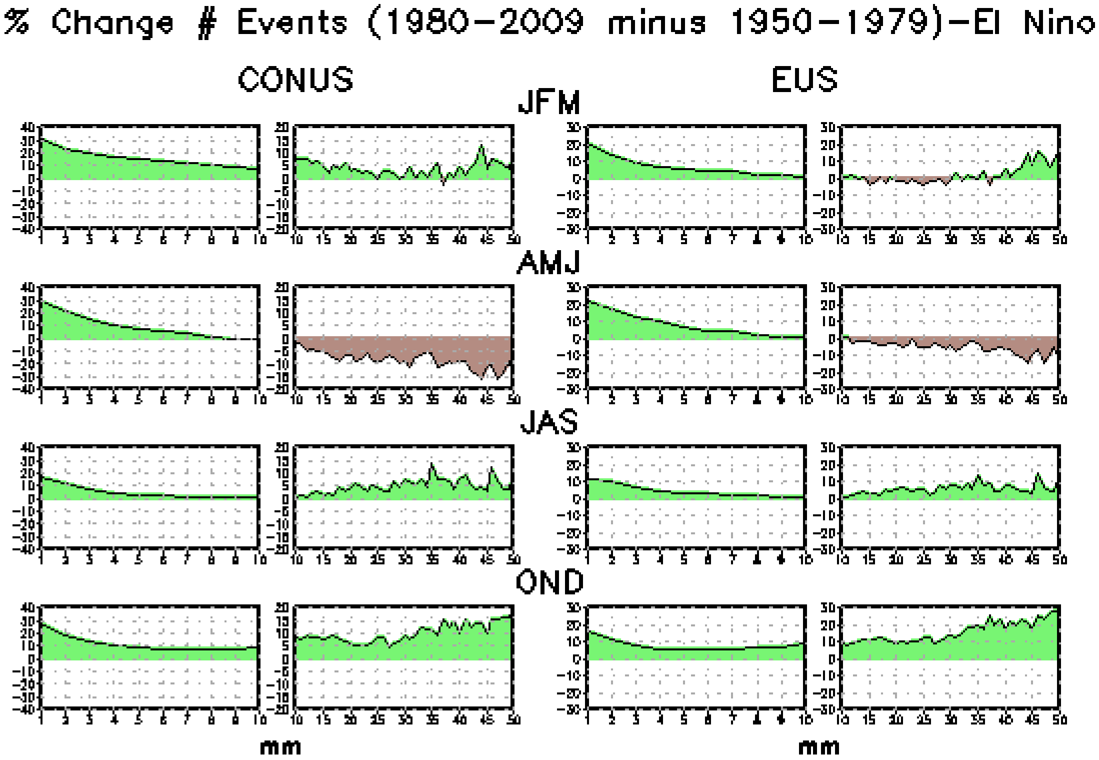

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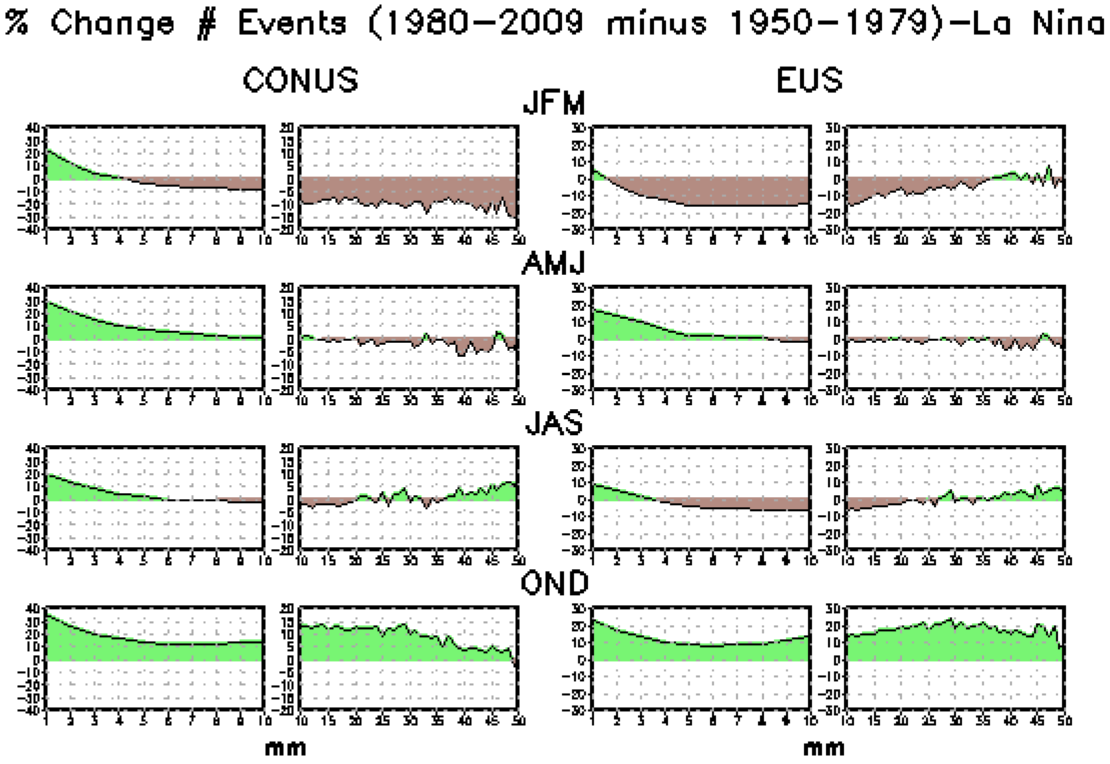

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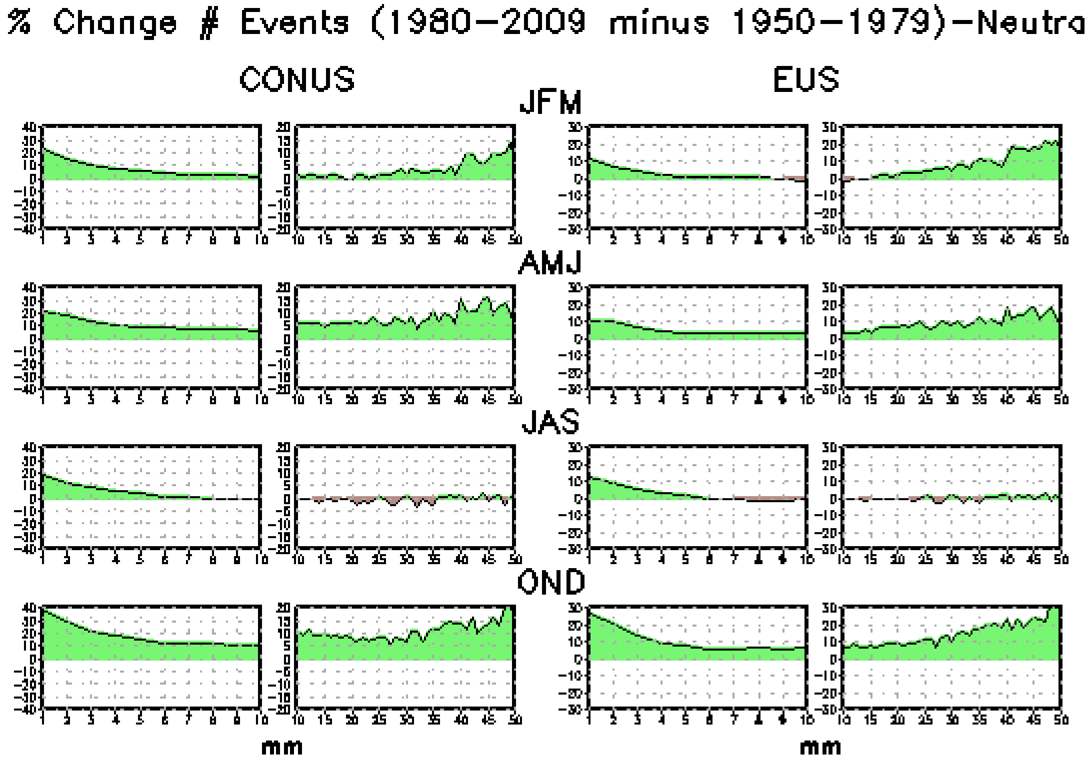

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