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LETTER

Contribution of large-scale circulation anomalies to changes in extreme precipitation frequency in the United States

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Abstract

The mean global climate has warmed as a result of the increasing emission of greenhouse gases induced by human activities. This warming is considered the main reason for the increasing number of extreme precipitation events in the US. While much attention has been given to extreme precipitation events occurring over several days, which are usually responsible for severe flooding over a large region, little is known about how extreme precipitation events that cause flash flooding and occur at sub-daily time scales have changed over time. Here we use the observed hourly precipitation from the North American Land Data Assimilation System Phase 2 forcing datasets to determine trends in the frequency of extreme precipitation events of short (1 h, 3 h, 6 h, 12 h and 24 h) duration for the period 1979–2013. The results indicate an increasing trend in the central and eastern US. Over most of the western US, especially the Southwest and the Intermountain West, the trends are generally negative. These trends can be largely explained by the interdecadal variability of the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation (AMO), with the AMO making a greater contribution to the trends in both warm and cold seasons.

1. Introduction

Extreme precipitation can exert large impacts on agriculture, ecosystems, and infrastructure. The most costly effect of extreme precipitation results from flooding, which can cause infrastructure damage, soil erosion, environmental pollution, ecosystem destruction, and even loss of lives (Spierre and Wake 2010). For example, the Great Flood of 1993 that was caused by persistent storms with voluminous rainfall over the upper Mississippi River Basin resulted in an estimated $18 billion in damage, making it one of the most costly natural disasters in the US (Kunkel *et al* 1994, Changnon 1996). It has been reported in recent literature, based on analyses of various datasets and over different time periods, that there has been an increase in extreme precipitation events across much of the contiguous US (Karl *et al* 1995, Karl and Knight 1998, Kunkel *et al* 1999, 2003, 2007, Kunkel 2003, Groisman *et al* 2005, 2012, Alexander *et al* 2006, Pryor *et al* 2009, Matonse and Frei 2013, Muschinski and Katz 2013). This increasing trend in extreme precipitation events in the US has been attributed to several natural and anthropogenic factors, including natural variability of the climate system (Kunkel 2003), the increasing number of fronts and extratropical and tropical cyclones over different parts of the US (Knight and Davis 2009, Kunkel *et al* 2010, 2012), and increasing evaporation and water vapor in the atmosphere due to human-induced greenhouse warming (Karl and Trenberth 2003, Trenberth *et al* 2003, Emori and Brown 2005, Willett *et al* 2007, Min *et al* 2011, Mishra *et al* 2012).

While the current debate about the attribution of extreme precipitation events has been centered on which factor, human activities or natural variability, is the main contributor to the increasing trend of extreme precipitation events, we will show here that the increase in extreme precipitation events in the US in the recent three decades is associated with the changes in large-scale atmospheric circulation patterns induced by sea-surface temperature (SST) changes over the North Pacific and the Atlantic Oceans. Our analyses focus on extreme precipitation events at hourly time scales, which are usually responsible for flash floods (Georgakakos 1986). Flash flooding can be particularly deadly because it can deliver an enormous amount of water in a matter of an hour, and it can happen over arid regions where storms are infrequent and the infrastructure for draining water is lacking. The lack of sufficient warnings and efficient emergency responses can exacerbate the adverse effects of short-duration extreme precipitation events (Ahern *et al* 2005). We consider extreme precipitation events in the US at sub-daily time scales of 1, 3, 6, 12 and 24 h (s) and explore the mechanisms for the recent trends of these events during the warm (May–October) and cold (November–April) seasons separately and in the context of atmospheric circulations.

2. Data and methods

Extreme precipitation events over the 1979–2013 period are identified using gridded hourly precipitation data obtained from the North American Land Data Assimilation System Phase 2 (NLDAS-2) forcing datasets, which has a high spatial resolution of 1/8 degree across central North America (Cosgrove *et al* 2003). This hourly precipitation dataset merges rain gauge and radar products, including Climate Prediction Center (CPC) daily gauge data across the US (Higgins *et al* 2000) with the Planning tool for Resource Integration, Synchronization and Management (PRISM) topographical adjustment (Daly *et al* 1994), and hourly Stage II Doppler Radar precipitation data. A detailed description of the data can be found at http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php. Like other gridded reanalysis products, the accuracy of the NLDAS-2 precipitation data for a given location and time is subject to the quality and availability of observations that vary spatially and temporally due to heterogeneity in instrument platforms, spatial coverage and record lengths. Nevertheless, NLDAS-2 is the best available gridded observational precipitation dataset for North America with the time and spatial resolution needed for the purpose of our analysis.

Our study focuses on extreme precipitation events that occur at sub-daily time scales. For a given time interval or duration (1, 3, 6, 12, and 24 h), cumulative precipitation amounts over that time interval (an event) are calculated, and all the data for the entire study period of 1979–2013 are used to derive a separate warm- and cold-season distribution of the cumulative precipitation for the given time interval. The 95th percentile of the distribution for each season is used as a threshold for extreme events in that season. In other words, a precipitation event for a given time interval in the warm or cold season is considered extreme when its cumulative precipitation amount exceeds the 95th percentile of all the same-season, same-duration events over the entire 34 year study period. We investigated the trends in the frequency of extreme precipitation events for the two seasons and reasons for those trends in the context of atmospheric circulations.

Large-scale atmospheric circulation patterns during the 1979–2013 period are identified using the global reanalysis dataset produced by the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) (Kanamitsu *et al* 2002). The NCEP-DOE global reanalysis has a horizontal resolution of 2.5° latitude × 2.5° longitude and a temporal resolution of 6 hours each day from 1 January 1979 to the present. The National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST dataset (Smith and Reynolds 2003, 2004) is also used for identifying the SST patterns over the North Pacific and Atlantic Oceans. The monthly Pacific Decadal Oscillation (PDO) index (Mantua *et al* 1997) is available from the website (http://atmos.washington.edu/~mantua/abst.PDO.html). The monthly Atlantic Multidecadal Oscillation (AMO) index (Enfield *et al* 2001) is available from the website (http://esrl.noaa.gov/psd/data/correlation/amon.us.data).

The empirical orthogonal function (EOF) technique is utilized to reveal the dominant patterns of the interannual variability in the extreme precipitation frequency for the warm and cold seasons. Regression analysis is also used to explore the relationship between the trends in the occurrence of sub-daily extreme precipitation events and anomalous atmospheric and oceanic variables. Specifically, SSTs, 500 hPa geopotential heights, and 850 hPa winds are regressed to the principle components (PCs) of each EOF mode to help explain the trends in extreme precipitation events.

3. Results

Over the last three decades (1979–2013), the occurrences of warm-season sub-daily extreme precipitation events generally increased across the central and eastern US, with larger upward trends found in the Northeast and the Southeast and smaller trends found over the Great Plains (figure 1). Over the western US, however, the results are mixed with upward trends in some areas such as Oregon and central California and downward trends in other areas, especially in the Intermountain West and the Southwest (figure 1). As the duration of the events increases from 1 h to 24 h, the magnitudes (both positive and negative) decrease while the spatial pattern remains. Similar spatial patterns in the eastern US are also found for the cold-season events, with the exception of the Florida Peninsula where the trends in extreme rainfall

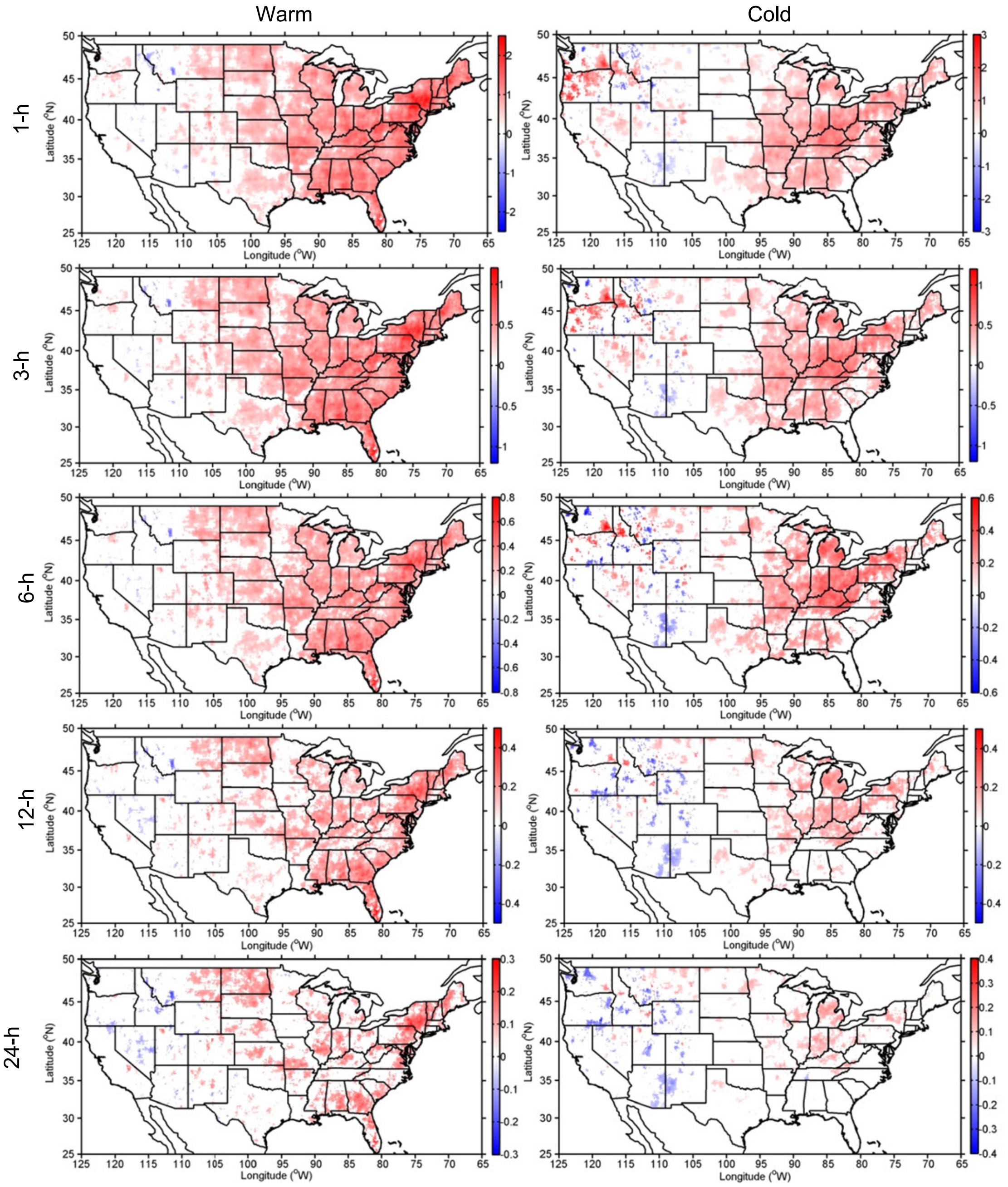

Figure 1. Total trends in the frequencies of the extreme precipitation events in warm (left) and cold (right) seasons for 1 h, 3 h, 6 h, 12 h, and 24 h durations (unit: events yr^{-1}). Only regions with the above 95% confidence level are shown.

frequencies are insignificant. The contrast between positive and negative trends in areas of the western US is also more pronounced in the cold season compared to the warm season. Kunkel *et al* (1999), (2003) and Pryor *et al* (2009) also found that over the 20th century, the frequency of annual daily extreme precipitation events increased in the central and eastern US and decreased over most of the western US. With the increasing duration of the events during the warm and cold seasons, the significant negative trends in extreme rainfall frequencies in the western US increase; the significant positive trends decrease.

The EOF analyses were applied separately to the frequencies of the extreme precipitation events for the different duration categories in the warm season and in the cold season to identify the prevailing spatial and temporal patterns of the variability. The results are shown for the 1 h duration events only; results for other durations are similar (figure 2).

The total variance explained by the first mode (EOF1) is 33.7% for the warm season (figure 2(a)) and 22.5% for the cold season (figure 2(b)). The EOF1 spatial patterns are similar to those of the total trends (figure 1), with predominantly positive anomalies over the central and eastern US, but some areas of negative anomalies in the Southwest and Intermountain West.

For both seasons, the EOF1 time coefficients or principal components (PC1s) show considerable

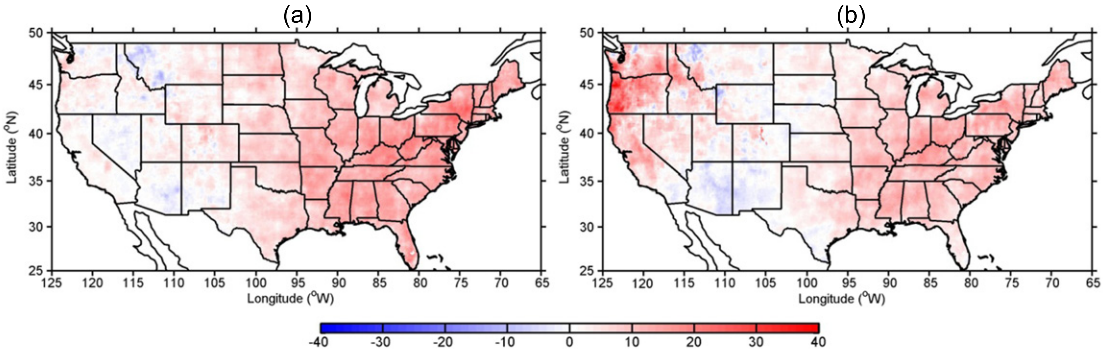

Figure 2. Spatial patterns of the first EOF modes of the frequencies of the 1 h duration extreme precipitation events in warm (a) and cold (b) seasons (unit: events yr^{-1}).

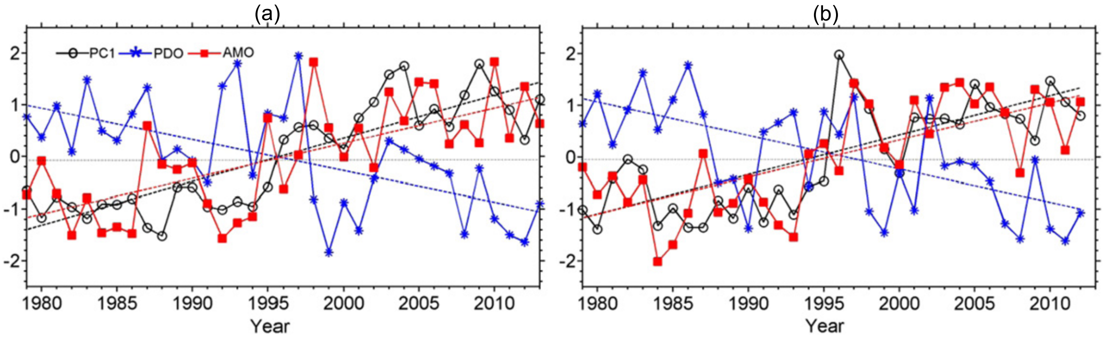

Figure 3. Time coefficients of the PC1 for the frequencies of the 1 h duration extreme precipitation events (black solid line), the normalized PDO index (blue solid line), and the normalized AMO index (red solid line) and their trends (dashed lines) in warm (a) and cold (b) seasons.

interannual variation and a significant upward trend, with positive values after 1996 and negative values prior to that (figure 3). The slope of the upward trend is 0.083 events yr^{-1} for the warm season, which is slightly larger than the cold-season slope of 0.076 events yr^{-1}. Previous studies identified major teleconnections between variations in regional precipitation extremes in the US and changes in SST characterized by the AMO, PDO and ENSO (McCabe *et al* 2004, DeFlorio *et al* 2013, Teengavarapu *et al* 2013). Correlation calculations here indicate that the PC1 is positively correlated (at 99.9% confidence level) to the AMO, with correlation coefficients of 0.67 for the warm season and 0.75 for the cold season. The PC1 is negatively correlated (at 99% confidence level) to the PDO, with correlation coefficients of −0.50 and −0.45 for the warm and cold seasons, respectively. The correlations between the PC1 and the Nino3.4 indices are −0.02 and −0.13 for the warm and cold seasons, respectively, but they are not significant. Consistent with the positive correlation, the normalized AMO time series also display a significant positive trend both in the warm season (0.068 events yr^{-1}) and in the cold season (0.072 events yr^{-1}) which closely match the PC1 trends (figure 3). The normalized PDO, on the other hand, displays a downward trend in the warm (−0.060 events yr^{-1}) and the cold (−0.065 events yr^{-1}) seasons (figure 3). All three trend lines intercept the horizontal axis around the same year (1996). The trends in the normalized Niño3.4 index are not significant.

Table 1. Coefficients of linear regression between the PC1 for the frequencies of the 1 h duration extreme precipitation events and the PDO and AMO indices in warm and cold seasons. $\text{PC1} = k_1 \times \text{PDO} + k_2 \times \text{AMO}$.

	k_1	k_2	Confidence level
Warm season	−0.2145	0.5647	>99.9%
Cold season	−0.1742	0.6772	>99.9%

The relationships between the PC1 and the two indices were further examined using multivariable linear regression. The negative (positive) regression coefficients (table 1) for the PDO (AMO) indices correspond to the negative (positive) correlation coefficients between the PC1 and the PDO (AMO) indices. Moreover, the magnitudes of the regression coefficients for the AMO index are larger than those for the PDO index, which is in agreement with the magnitudes of the correlation coefficients. It indicates that the AMO index makes a greater contribution to the PC1 trends than the PDO index.

The above analysis has clearly linked the variation and trend of the PC1 to those of the AMO and the

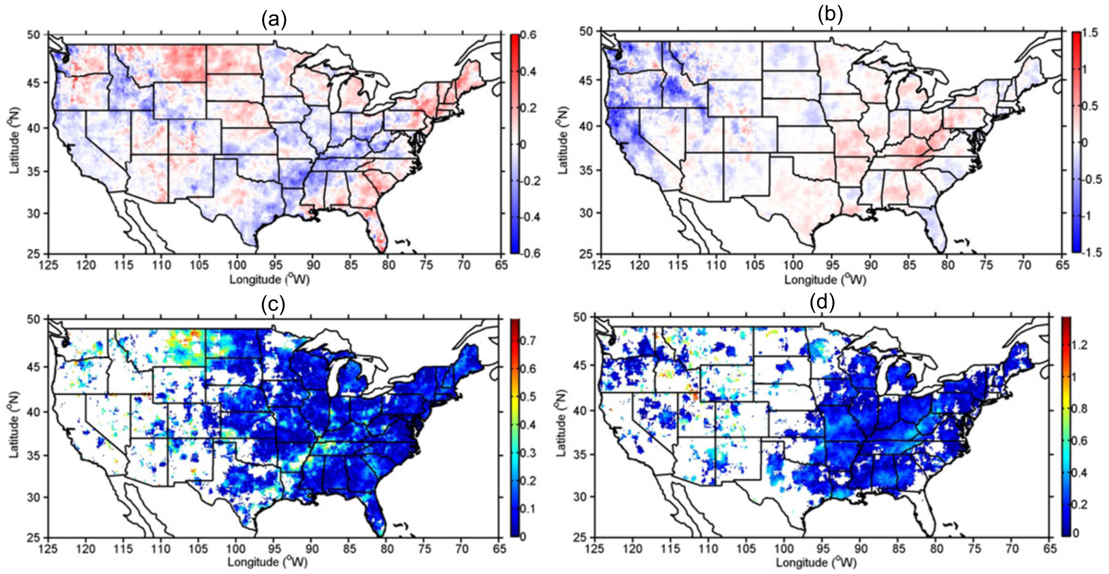

Figure 4. Residual trends (a), (b) in the frequencies of the 1 h duration extreme precipitation events (events yr^{-1}) and the ratios of the residual trends to the total trends (c), (d) in the warm (a), (c) and cold (b), (d) seasons (unit: events yr^{-1}).

PDO. The question is how much of the total trend can be explained by the first mode? The answer to this question is location-dependent. Although there is considerable variation across the domain, the residual trends (figures 4(a) and (b)) are small in most regions, and the ratios of the residual trends to total trends (figures 4(c) and (d)) are generally below 20%, with a domain-average of 7.4% for the warm season and 20.2% for the cold season.

To understand the trends explained by the first EOF mode in the context of atmospheric circulation anomalies, the SSTs, 500 hPa geopotential heights, and 850 hPa wind vectors were regressed to the PC1s (figure 5). The SST regression map shows a spatial pattern indicative of the negative phase of the PDO over the North Pacific Ocean and the positive phase of the AMO over the North Atlantic Ocean (figures 5(a) and (b)). The result is consistent with the correlation between the PC1 and the PDO and AMO indices. Corresponding to the SST regression pattern are anomalous highs over the northern and west-central Pacific Ocean, the tropical western Atlantic Ocean, and over northeastern North America; and anomalous lows over the north-central Atlantic Ocean and over western North America (figures 5(c) and (d)). In the warm season, the strengthening Bermuda High (figure 5(c)) and the enhanced southerly flows (figure 5(e)) on its west side help bring warm moist air into the Great Lakes region and the Northeast, increasing dew point temperatures in these regions (figure 5(g)). The anomalous 850 hPa southerly winds from the Gulf of Mexico into the Southeast also contribute to the increasing dew point temperatures there (figures 5(e) and (g)). Lepore *et al* (2015) suggested the hourly extreme precipitation intensity is proportional to dew point temperature. The regions with increasing dew point temperature would imply more extreme precipitations. Over the western US, the anomalous winds are weak and variable, and the conditions are affected more by local factors.

Compared with the warm season, the anomalous highs over the Atlantic Ocean and northeastern North America in the cold season are weakened while those over the eastern Pacific are strengthened somewhat. The anomalous low over the western US is strengthened considerably (figure 5(d)). The anomalous southerly winds from the Gulf of Mexico and the easterly winds from the eastern Atlantic Ocean supply the central and eastern US with ample moisture, increasing the chance for extreme precipitation events there (figures 5(f) and (h)). The anomalous trough in the Pacific Northwest allows for the transport of moisture from the Pacific Ocean by southwesterly anomalous flows into Oregon and lower Washington, enhancing the chance for extreme precipitation there.

4. Discussion

The increasing trend in extreme precipitation events in the US has been attributed, in large part, to the increase in greenhouse gases. However, the contributions from internal low-frequency variability in the climate system are not well understood. In this study, we have quantified the contributions of the AMO and PDO to the trends in the past three decades in the extreme precipitation events that occur at hourly time scales and lead to flash flooding. We have shown that the phase reversals of the AMO and PDO in the late 1990s are favorable for an increasing trend in these types of extreme precipitation events over the central and eastern United States. Matonse and Frei (2013)

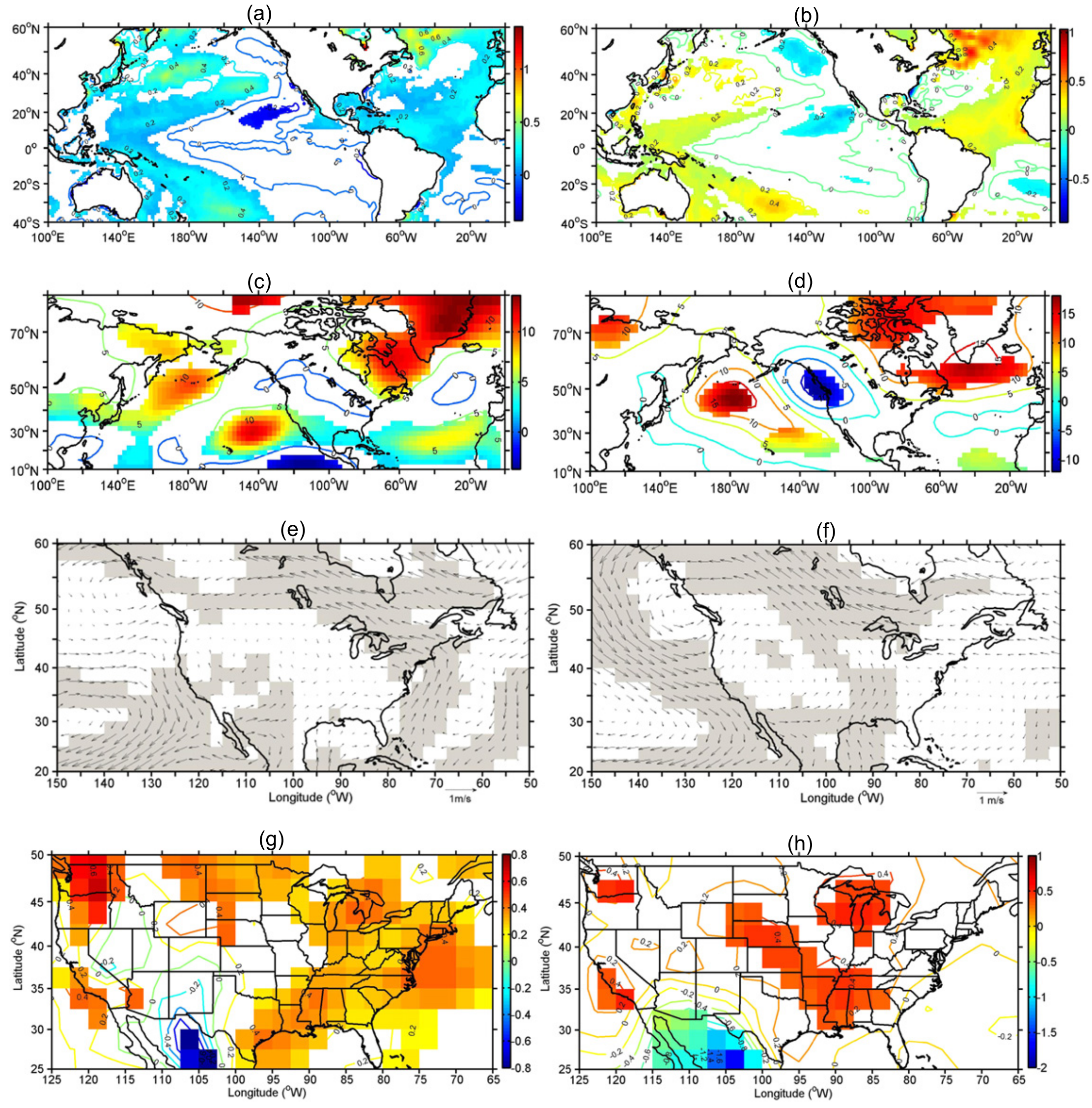

Figure 5. The anomalous sea-surface temperature (SST) (°C) (a), (b), 500 hPa geopotential height (gpm) (c), (d), 850 hPa wind vector (e), (f) fields and 850 hPa dew point temperature (g) (h) regressed to the PC1 of the 1 h extreme rainfall frequencies in the warm (a), (c), (e), (g) and cold (b), (d), (f), (h) seasons for the period 1979–2013. The filled and shaded regions are significant at the 95% confidence level.

found an accelerated increase in the frequency of 4 day extreme precipitation events in southern New York State during the warm season since the mid-1990s, but a decrease during the cold season, which agrees with our results. Knight and Davis (2009) suggested that the extreme precipitation produced by tropical cyclones in the southeastern US has been increasing over the period 1972–2007. Kunkel *et al* (2010) also recorded an increase in heavy precipitation associated with tropical cyclones across the eastern US since 1994 and attributed it to the increasing number of hurricanes making landfall. The SST change over the tropical Atlantic Ocean induced by the AMO can influence the tropical cyclone activity (Landsea *et al* 1999, Goldenberg *et al* 2001). Our conclusion that the phase reversal in the AMO in the mid-1990s contributes to the increasing extreme precipitation events across the eastern US during the warm season is consistent with the aforementioned results. Kunkel (2003) also suggested that the natural variability at interdecadal time scales contributed to the recent higher frequency of extreme precipitation events. Despite our conclusion that the recent increasing trend in extreme precipitation events across the US is mainly associated with the internal climate variability indicated by the AMO and PDO, it is unlikely that natural variability alone can explain the long-term trend without considering the contributions from global warming due to increased greenhouse gas emissions (Karl and Trenberth 2003, Trenberth *et al* 2003, Emori and Brown 2005, Willett *et al* 2007, Spierre and Wake 2010, Min *et al* 2011, Mishra *et al* 2012).

5. Summary

This study examined the trends in the last three decades of the frequencies of warm- and cold-season extreme precipitation events at sub-daily time scales and attributes the opposite trends between the western and central/eastern US to the interdecadal variability of the PDO and AMO global circulation indices.

The trends display a similar spatial pattern for the warm and cold seasons, where generally positive trends are found in the central and eastern US and negative trends characterize the western US. This spatial pattern remains as the duration of the extreme precipitation events increases from 1 h to 24 h, but the magnitudes of the trends decrease. The first EOF mode yields a spatial pattern that closely resembles the spatial pattern of the trend, and the PC1 displays an increasing trend and significant variability at the interannual and interdecadal time scales. The trend and time variations of the PC1 are found to be positively correlated to the AMO index and negatively correlated to the PDO index, linking the increasing (decreasing) extreme sub-daily precipitation events in the central and eastern US (most areas in the western US) to the negative phase of the PDO index and the positive phase of the AMO index. The contribution of the AMO index to the trend in the sub-daily extreme precipitation events is greater than that of the PDO index. The first modes in the warm and cold seasons account for more than 80% of total trends in most regions of the US.

The anomalous SSTs related to the PDO and AMO indices produce anomalous highs over the North Pacific and the Atlantic Oceans and northeast North America. The anomalous southerly and southeasterly winds associated with the anomalous Atlantic and northeast North America highs transport warm, moist air into the eastern US, increasing the chances for extreme precipitation events. The anomalous trough in the northwestern US, on the other hand, leads to more favorable conditions for extreme precipitation in the cold season there.

The hourly NLDAS-2 precipitation dataset has some limitations, such as the heterogeneous distribution of gauge stations and radar sites and data sources with different record lengths. Moreover the low resolution of the data tends to underestimate local factors such as terrain and vegetation. But those limitations unlikely affect the confidence in the results of the current analyses. Our study emphasizes the importance of the AMO and the PDO to the prediction of the trend in extreme precipitation at sub-daily time scales and identifies the relative contribution of the two indices to the trend. The results from this study may be used for improving predictions of trends and interdecadal variability of the frequency of sub-daily extreme precipitation events and associated flash flooding.

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