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Relationships of the symmetric and asymmetric components of ENSO to US extreme precipitation

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Abstract

We used 35-year (1979–2013) hourly rainfall data from the North American Land Data Assimilation System (NLDAS-2) to examine the relationships of the symmetric and asymmetric components of two types of El Niño-Southern Oscillation (ENSO) (El Niño and El Niño Modoki) episodes with occurrences of extreme precipitation events across the United States. During the cold season, the symmetric impacts of El Niño and El Niño Modoki are more significant than during the warm season. The asymmetric components associated with El Niño during the two seasons are comparable, while the asymmetric components associated with El Niño Modoki during the warm season are more significant than those during the cold season. The connections between the symmetric and asymmetric components of the two types of ENSO and extreme precipitation occurrences are related to atmospheric moisture convergence patterns that tend to occur in response to the anomalous large-scale atmospheric circulations during the ENSO episodes.

Keywords: El Niño; El Niño Modoki; extreme precipitation events; teleconnections; nonlinearity

1. Introduction

Extreme precipitation resulting from short-duration convective storms can lead to flash floods that have the potential for causing great damage to ecosystems, the economy, and society (Easterling *et al.,* 2000). The El Niño-Southern Oscillation (ENSO) is the most influential ocean–atmosphere phenomenon over the tropical Pacific Ocean, which affects the global precipitation pattern (Dai and Wigley, 2000). Previous studies have identified the relationship between ENSO and United States (US) extreme precipitation. During El Niño years, wintertime extreme precipitation occurs more frequently over the central Rockies, the Gulf Coast, Florida, the Southwest and the central US, and less frequently over the Ohio/Mississippi River Valley and Red River basin (Gershunov and Barnett, 1998; Cayan *et al.,* 1999; Becker *et al.,* 2009; Higgins *et al.,* 2010; Schubert *et al.,* 2010; Shang *et al.,* 2011; Deflorio *et al.,* 2013; Goly and Teegavarapu, 2014). A nearly opposite pattern occurs during La Niña years, which is defined as a symmetric relationship (e.g. Brönnimann *et al.,* 2007). ENSO also influences US summertime extreme precipitation, with El Niño episodes typically leading to more occurrences of summertime extreme precipitation events over the northern Rocky Mountains (Becker *et al.,* 2009); the opposite occurs during La Niña years, again a symmetric relationship.

The relationship of El Niño and La Niña to extreme precipitation in the US can be symmetric in some regions, but asymmetric in other regions. Shubert *et al.* (2008) fit a generalized extreme value distribution to principal components of US wintertime extreme precipitation anomalies, separately for La Niña, neutral, and El Niño years, and found symmetric relationships over the Gulf and East Coasts and asymmetric relationships over the Southwest. Using a Bayesian regional extreme value model, Sun *et al.* (2015) noted that the asymmetric relationships of ENSO to extreme precipitation in autumn and winter occur in the central and western US, and the symmetric relationships occur in the southern US. Using two types of nonlinear statistical models with fixed and varying Niño 3.4 breakpoints, Cannon (2015) found when Niño 3.4 breakpoints are 0.4 °C, the relationship between ENSO and wintertime US extreme precipitation shows a strong asymmetric feature.

Recently, a new El Niño pattern has received increased scrutiny, namely the central Pacific El Niño or El Niño Modoki pattern, which is characterized by warm sea-surface temperatures (SSTs) over the central Pacific Ocean sandwiched by cold SSTs over the tropical eastern and western Pacific Ocean (Kao and Yu, 2009). El Niño Modoki episodes can have a different relationship to the occurrence of US extreme precipitation events than El Niño episodes, as shown in the studies of Ning and Bradley (2015) and Yu *et al.* (2017). Whether the relationships of El Niño Modoki and La Niña Modoki episodes to US extreme precipitation are symmetric or asymmetric remains an issue.

In this study, we investigate and compare the symmetric and asymmetric relationships of El Niño/La Niña and El Niño Modoki/La Niña Modoki episodes to sub-daily US extreme precipitation events during both cold and warm seasons for the 1979–2013 period using the method of Hoerling *et al.* (1997). Our study differs from previous studies in five aspects. First, we investigate the symmetric and asymmetric relationships during both warm and cold seasons, in contrast to previous studies that have focused on the cold season only. Second, we identify the symmetric and asymmetric influence mechanisms associated with both El Niño/La Niña and El Niño Modoki/La Niña Modoki episodes. Third, we utilize a composite method for the opposite phases of El Niño and El Niño Modoki instead of statistical models used in previous studies. Fourth, we use hourly gridded precipitation data with a spatial resolution of 1/8 degree covering the contiguous US, in contrast to sparse station data across the US used in previous studies. Finally, we examine extreme precipitation events over sub-daily durations ranging 1–24 h, compared with previous studies that primarily focused on daily extreme precipitation events.

2. Data and methods

The hourly precipitation data used in this study were derived from the second generation of the North American Land Data Assimilation System (NLDAS-2). NLDAS-2 is a high-resolution atmosphere and land-surface hydrology dataset spanning the 1979-present period and covering the contiguous US, southern Canada, and northern Mexico with a spatial resolution of 1/8 degree (Cosgrove *et al.,* 2003; Xia *et al.,* 2012). A detailed description of the data can be found at http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php.

From the NLDAS-2 dataset, numbers of sub-daily extreme precipitation occurrences with durations of 1, 3, 6, 12, and 24 h were identified over the 1979–2013 period during the warm (May through October) and cold (November through April) seasons. A precipitation event was defined 'extreme' if the accumulated precipitation amount during the specified time interval exceeded the 1979–2013 95th percentile for the warm or cold season in which it occurred. In addition, 500-hPa heights, 850-hPa wind fields, 1000–500 hPa averaged moisture convergence and 1000–500 hPa averaged vertical velocities from the National Centers for Environmental Prediction – Department of Energy (NCEP-DOE) (Kanamitsu *et al.,* 2002) and the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST dataset (Smith and Reynolds, 2003, 2004) were used to identify atmospheric circulation and moisture convergence patterns conducive to extreme precipitation that are associated with the two types of ENSO. The conventional El Niño or eastern Pacific El Niño is represented by the Niño 3.4 index derived from the NOAA-CPC (http://www.cpc.ncep.noaa.gov/data/indices/). The El Niño Modoki index is derived from the Japan Agency for Marine-Earth Science and Technology (available at http://www.jamstec.go.jp/frsgc/research/d1/iod/modoki_home.html.en).

For composite analyses, El Niño, La Niña, El Niño Modoki, and La Niña Modoki episodes were chosen based on the threshold of one standard deviation of Niño 3.4 and El Niño Modoki indices during the warm and cold seasons (Figure S1). The selected years for the different episodes are as follows: warm season El Niño (1982, 1987, 1997, 2009); cold season El Niño (1982–1983, 1986–1987, 1997–1998, 2006–2007); warm season La Niña (1985, 1988, 1999, 2010); cold season La Niña (1984–1985, 1988–1989, 1998–1999; 1999–2000); warm season El Niño Modoki (1991, 1994, 2002, 2004); cold season El Niño Modoki (1990–1991; 1994–1995; 2002–2003; 2004–2005; 2009–2010); warm season La Niña Modoki (1983, 1998, 2008); cold season La Niña Modoki (1983–1984, 2000–2001, 2007–2008, 2010–2011, 2011–2012).

An 8-year high-pass filter was applied to the time series of the number of sub-daily extreme precipitation events to attenuate low-frequency variations and maintain the interannual variability associated with the 3–7 years period of ENSO. Linear trends were also removed from the extreme precipitation occurrence data to filter out long-term global warming effects. Extreme precipitation occurrence anomalies for the warm and cold seasons were computed by subtracting 1979–2013 extreme precipitation occurrence climatologies for the warm and cold seasons from the time series of the detrended 8-year high-pass filtered occurrence data at each grid point. Finally, using the method of Hoerling *et al.* (1997), differences in the number of extreme precipitation occurrence anomalies between the composite El Niño and La Niña episodes were computed. These differences represent the symmetric component of the El Niño/La Niña association with extreme precipitation. The sums of the number of extreme precipitation occurrence anomalies over the composite El Niño and La Niña episodes were also computed; they represent the asymmetric component of the El Niño/La Niña association with extreme precipitation. The Mann–Whitney U-test (Mann and Whitney, 1947) was employed to assess the statistical significance of the symmetric and asymmetric components of El Niño and La Niña. This statistical significance test is more appropriate for assessing non-Gaussian type variables like extreme precipitation occurrences than the more commonly used t-test. A similar analysis was also applied to the extreme precipitation occurrences during El Niño Modoki and La Niña Modoki episodes.

3. Results and discussion

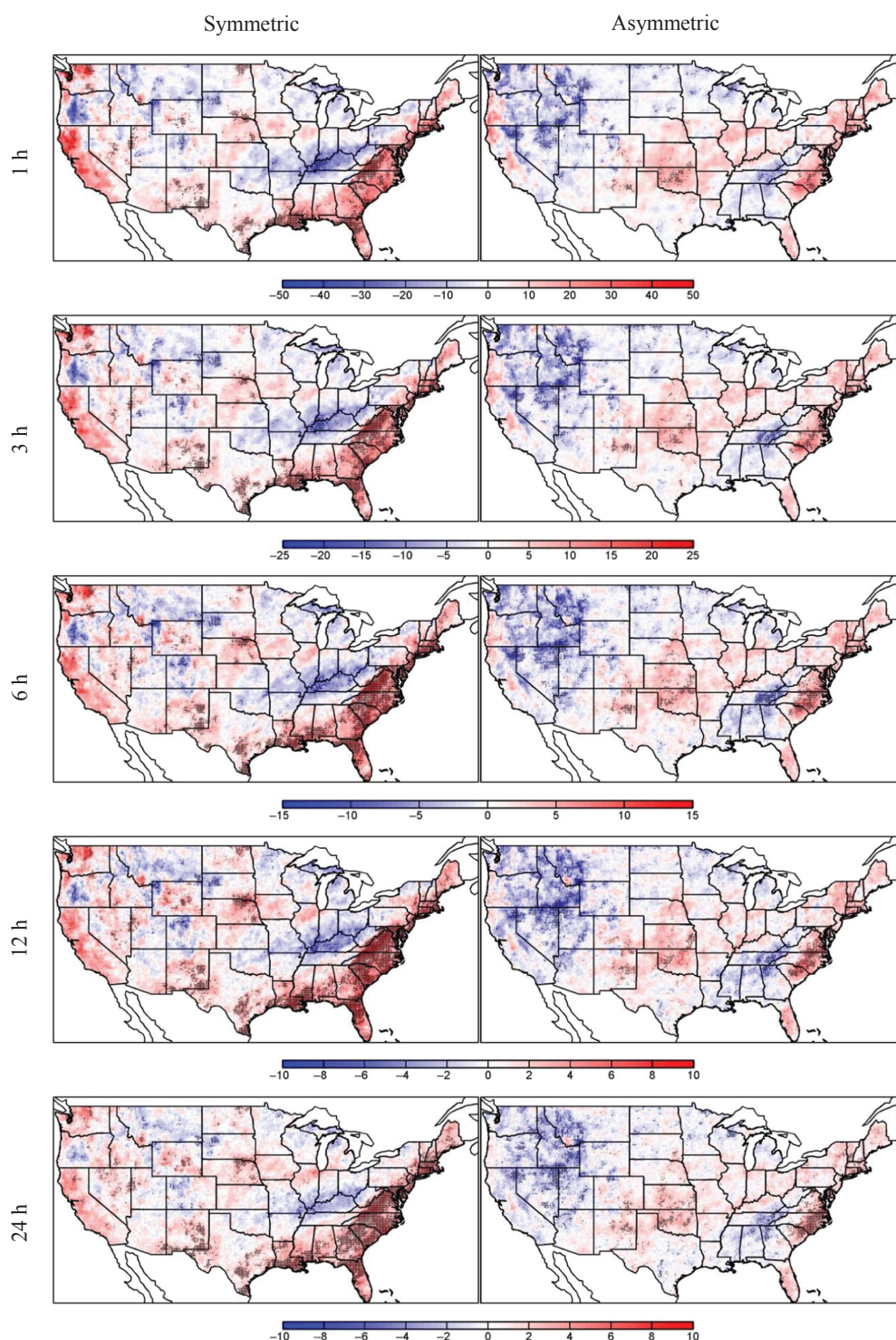### 3.1. Symmetric and asymmetric relationships

The symmetric and asymmetric relationships of El Niño and La Niña to the occurrences of sub-daily US extreme

Symmetric   Asymmetric
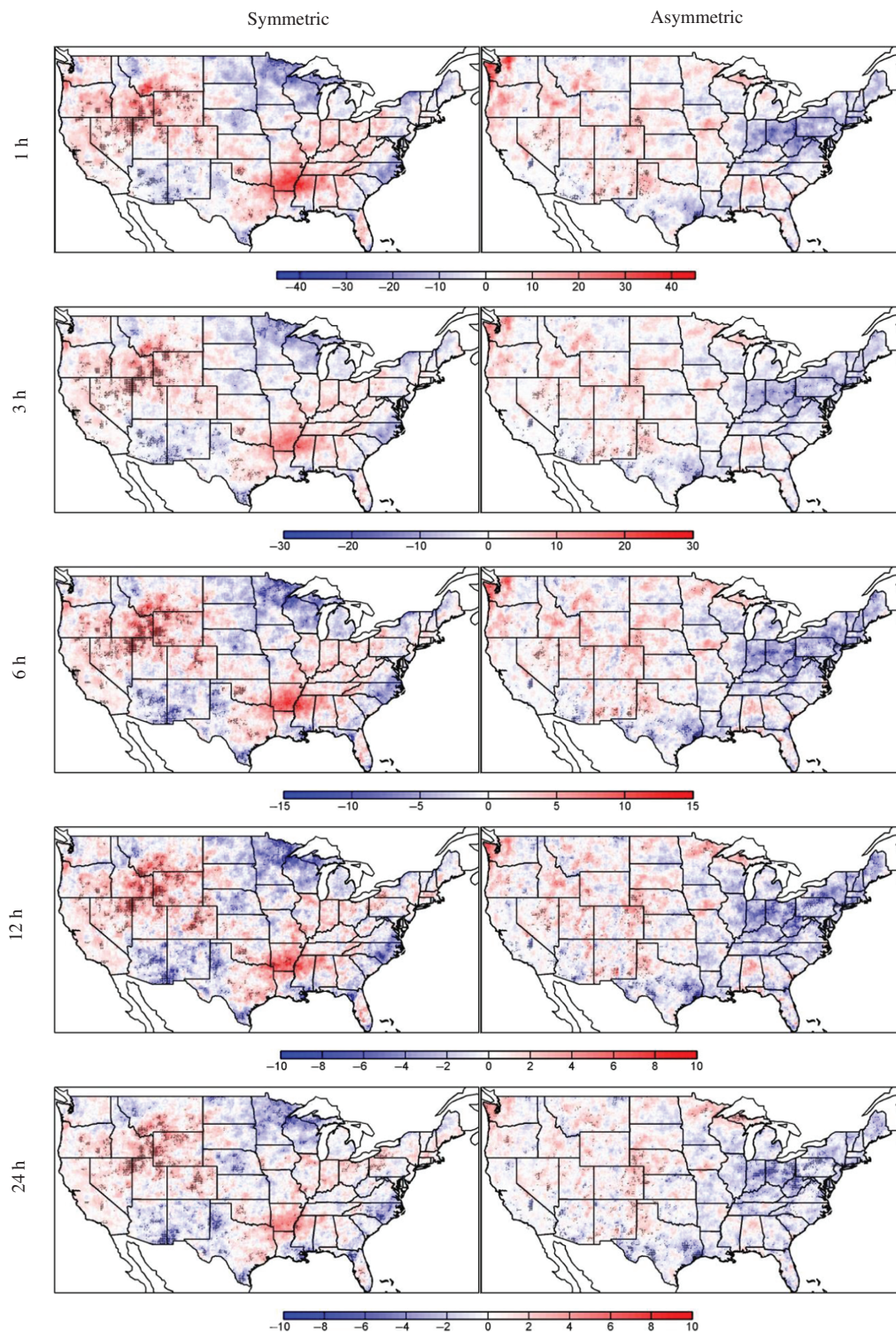
Figure 1. The symmetric and asymmetric relationships of El Niño and La Niña to US extreme precipitation occurrences lasting 1, 3, 6, 12, or 24 h during the warm season (May–October). The units are differences in (symmetric component) or sums of (asymmetric component) the number of extreme precipitation occurrence anomalies for the composite El Niño and La Niña episodes. The gray dotted areas indicate locations where positive or negative values are statistically significant (90% confidence level). See the 1-h extreme precipitation climatological summaries in Figures S2 and S3, respectively, as an aid in interpreting the symmetric and asymmetric relationships.

precipitation events during the warm and cold seasons are shown in Figures 1 and 2. During the warm season, the symmetric components are characterized by more widespread areas of statistically significant positive values over the western US than over the

eastern US (Figure 1). This suggests that the relative impact of El Niño compared to La Niña on warm season sub-daily extreme precipitation events tends to be more prominent over the western US than over the eastern US. Statistically significant negative values are found

Figure 2. The symmetric and asymmetric relationships of El Niño and La Niña to US extreme precipitation occurrences lasting 1, 3, 6, 12, or 24 h during the cold season (November–April). The units are differences in (symmetric component) or sums of (asymmetric component) the number of extreme precipitation occurrence anomalies for the composite El Niño and La Niña episodes. The gray dotted areas indicate locations where positive or negative values are statistically significant (90% confidence level). See the 1-h extreme precipitation climatological summaries and standard deviations in Figures S2 and S4, respectively, as an aid in interpreting the symmetric and asymmetric relationships.

over portions of the southwestern US, the central Great Plains, the western Great Lakes region, and North Carolina. These results are consistent with the composite of summer daily precipitation frequencies between El Niño and La Niña years as discussed in Becker *et al.* (2009).

The statistically significant positive and negative values associated with the warm season asymmetric components shown in Figure 1 are found primarily over the central and northeastern US, respectively. However, they are more localized and much less prominent than what is observed in the symmetric components.

Compared with the warm season, the symmetric and asymmetric relationships of El Niño and La Niña to cold season sub-daily extreme precipitation occurrences are more significant across the US. (Figure 2). The locations where the number of sub-daily extreme precipitation events during El Niño episodes is significantly greater than what typically occurs during La Niña episodes (i.e. the symmetric component) are found along the Atlantic Coast, the Gulf Coast, over Florida, and over portions of the southwestern and central US. Significantly fewer extreme precipitation events occur during El Niño episodes compared to La Niña episodes over the Ohio River Valley and portions of the Rocky Mountain region. For the asymmetric component, both El Niño and La Niña episodes are associated with significantly fewer extreme precipitation events over the Intermountain West, and more events along the mid-Atlantic Coast.

The symmetric and asymmetric relationships of El Niño Modoki and La Niña Modoki to sub-daily US extreme precipitation occurrences are shown in Figures 3 and 4. During the warm season, the symmetric relationship shows statistically significant positive anomalies over isolated areas in the states of Washington, Texas, Georgia, and South Carolina; and negative anomalies over numerous isolated areas in the western US (Figure 3). The warm season asymmetric relationship shows statistically significant negative anomalies over a relatively small area in Colorado and positive anomalies over localized areas near the Gulf Coast. Warm season El Niño Modoki/La Niña Modoki episodes appear to be more strongly associated with shorter duration extreme precipitation occurrences.

During the cold season, the symmetric relationships of El Niño Modoki/La Niña Modoki episodes to extreme precipitation occurrences are most significant over the southwestern US, the southern Atlantic Coast, southern Florida and the Mississippi River estuary where positive anomalies occur (Figure 4). Statistically significant negative anomalies occur over the northern Great Plains and the western Great Lakes region. The statistically significant negative values tend to become less prominent for longer duration extreme precipitation events. The asymmetric components of El Niño Modoki/La Niña Modoki episodes show significant positive values over portions of the northern Great Plains and the southeastern US; and significant negative values over isolated areas of the northwestern US and Oklahoma.

3.2. Influence mechanisms

To explain the symmetric and asymmetric relationships of the two types of ENSO to the frequencies of sub-daily US extreme precipitation events, composites of SSTs and atmospheric variables including 500-hPa geopotential heights, 850-hPa wind fields, 500–1000 hPa averaged moisture convergence, and 500–1000 hPa averaged vertical velocity were generated. The composite used to explain how cold season El Niño/La Niña episodes asymmetrically influence extreme precipitation events in the United States is discussed in detail below.

The asymmetric component of the SST anomalies associated with cold season El Niño/La Niña episodes displays a weak El Niño pattern over the Pacific Ocean and a north-to-south negative–positive–negative pattern over the North Atlantic Ocean (Figure 5(a)). The weak El Niño pattern excites a 500 hPa Rossby wave train propagating from the subtropical North Pacific Ocean to North America and on to the North Atlantic Ocean (Figure 5(b)), with negative height anomalies extending from the North Pacific Ocean southeastward to the southwestern US. A maximum height anomaly is centered over eastern North America. The anomalous height pattern over North America resembles the negative phase of the tropical Northern Hemisphere (TNH) pattern (Mo and Livezey, 1986) while the anomalous heights over the North Atlantic Ocean resemble the positive phase of the Northern Atlantic Oscillation (NAO).

The positive 500 hPa height anomalies and anticyclonic cell over eastern North America shown in Figure 5(b) are conducive to the transport of warm moist air to the eastern and southern US (Figure 5(c)) and the convergence of moisture (Figure 5(d)) coupled with rising motion (Figure 5(e)) in these areas. Slight moisture divergence and sinking motion characterize the northwestern US. Overall, these composite patterns are consistent with more (less) frequent cold season extreme precipitation occurrences over the southeastern (northwestern) US during both El Niño and La Niña episodes, as suggested in Figure 2.

Similar mechanism explanations can be applied to the other symmetric and asymmetric components for the two types of ENSO episodes during warm and cold seasons.

4. Summary and conclusions

The relationships between the symmetric and asymmetric components of two types of ENSO to occurrences of sub-daily extreme precipitation events in the US during warm and cold seasons were investigated using hourly precipitation data from the NLDAS-2 dataset. The symmetric components during El Niño and La Niña episodes identified in this study agree with previous studies (Gershunov and Barnett, 1998; Cayan *et al.*, 1999; Becker *et al.*, 2009; Higgins *et al.*, 2010; Schubert *et al.*, 2010; Shang *et al.*, 2011; Deflorio *et al.*, 2013; Goly and Teegavarapu, 2014). Results from this study indicate the asymmetric components during the warm and cold seasons tend to occur over the central, northeastern, and northwestern US, and over the central Atlantic Coast. These results are not consistent with the findings of Shubert *et al.* (2008) and Sun *et al.* (2015), which were based on statistical model approaches as opposed to the composite analyses used in this study.
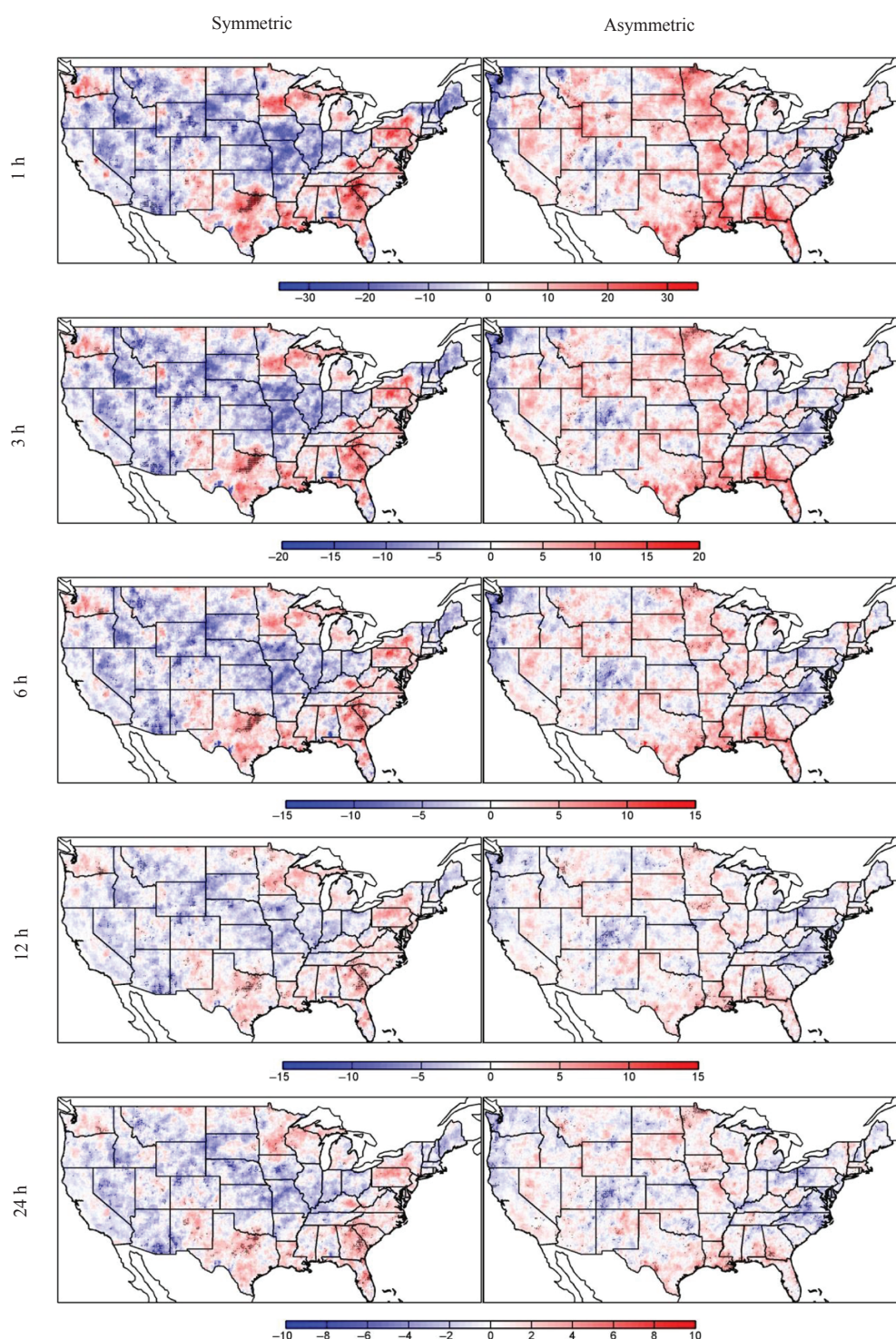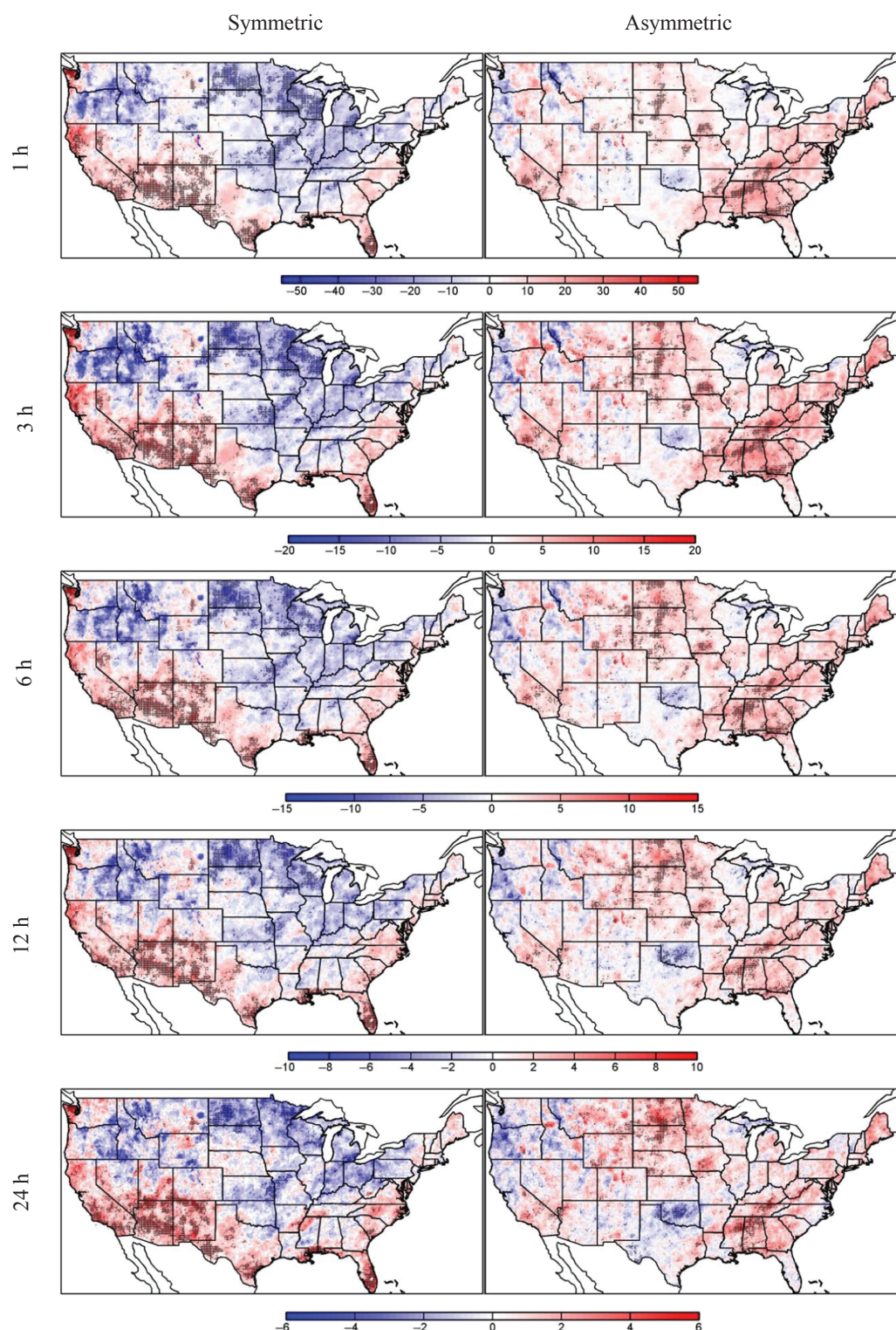
Figure 3. The symmetric and asymmetric relationships of El Niño Modoki and La Niña Modoki to US extreme precipitation occurrences lasting 1, 3, 6, 12, or 24 h during the warm season (May–October). The units are differences in (symmetric component) or sums of (asymmetric component) the number of extreme precipitation occurrence anomalies for the composite El Niño Modoki and La Niña Modoki episodes. The gray dotted areas indicate locations where positive or negative values are statistically significant (90% confidence level). See Figure S3 for the 1-h extreme precipitation occurrence standard deviations for the El Niño Modoki and La Niña Modoki episodes as an aid in interpreting the symmetric and asymmetric relationships.

Shubert *et al.* (2008) noted cold season asymmetric components over California during El Niño and La Niña episodes while Sun *et al.* (2015) did not find significant asymmetric components in the western US.

The current analysis revealed, for the first time, the linkage between symmetric and asymmetric components of El Niño Modoki and La Niña Modoki episodes and US warm and cold season sub-daily extreme precipitation occurrences. During the warm season, the symmetric components show statistically significant positive values over portions of Texas, Georgia, and South Carolina; and statistically

Figure 4. The symmetric and asymmetric relationships of El Niño Modoki and La Niña Modoki to US extreme precipitation occurrences lasting 1, 3, 6, 12, or 24 h during the cold season (November–April). The units are differences in (symmetric component) or sums of (asymmetric component) the number of extreme precipitation occurrence anomalies for the composite El Niño Modoki and La Niña Modoki episodes. The gray dotted areas indicate locations where positive or negative values are statistically significant (90% confidence level). See Figure S4 for the 1-h extreme precipitation occurrence standard deviations for the El Niño Modoki and La Niña Modoki episodes as an aid in interpreting the symmetric and asymmetric relationships.

significant negative values over numerous isolated areas in the western US. The warm season asymmetric components show localized significant positive values over the Gulf Coast and localized significant negative values over portions of Colorado. During

the cold season, the symmetric components feature significant negative values over portions of the northern US and significant positive values over portions of the southern US. The cold season asymmetric components feature statistically significant positive
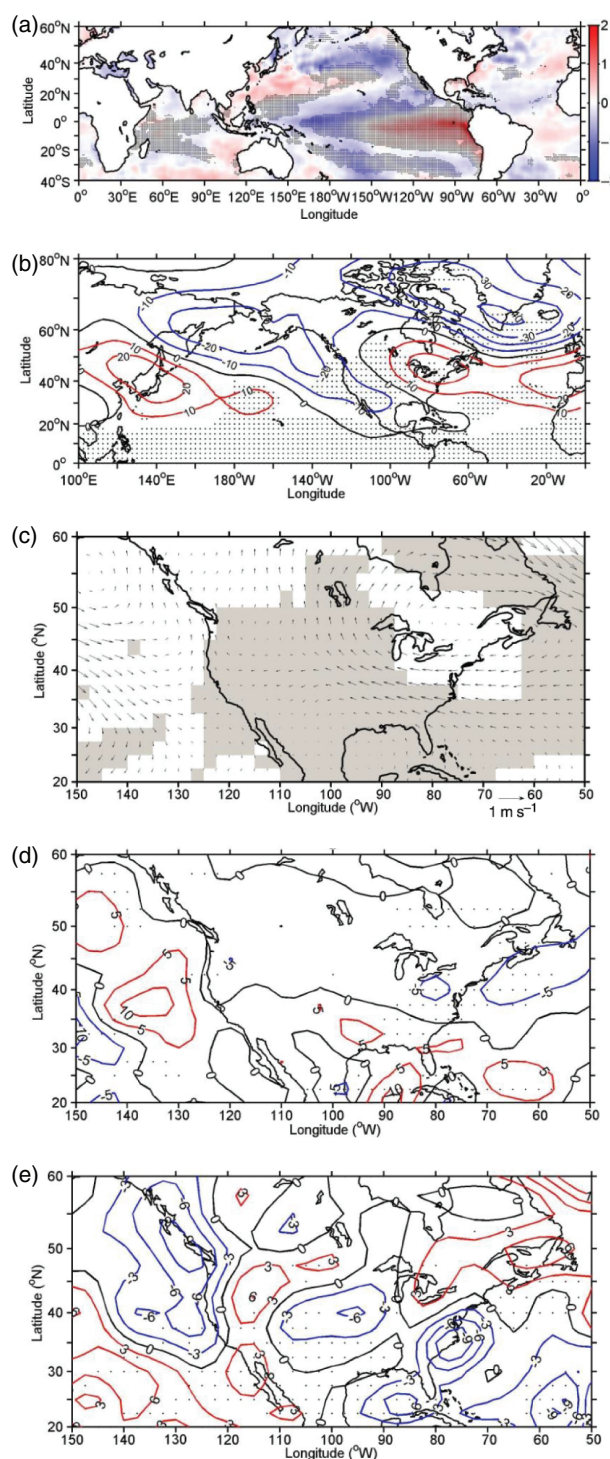
Figure 5. The composite of the asymmetric component of cold season El Niño/La Niña episodes: (a) Sea surface temperature (SST) anomalies (C); (b) 500-hPa geopotential height anomalies (m); (c) 850-hPa wind anomalies; (d) 1000−500 hPa averaged moisture convergence anomalies (10^{-7} g kg^{-1} s), where positive (negative) values indicate moisture convergence (divergence); (e) 1000−500 hPa averaged vertical velocity anomalies (10^{-3} Pa s^{-1}), where positive (negative) values indicate descent (ascent). Dotted areas and gray boxes indicate locations where the anomalies are statistically significant (90% confidence level). Anomalies were computed based on 8-year high-pass filtered and detrended data.

values over portions of the northern Great Plains and the southeastern US; and negative values over Oklahoma. The relationships of extreme precipitation occurrences to El Niño Modoki/La Niña Modoki episodes are considerably stronger during the cold season than during the warm season, with less isolated and more widespread areas of statistically significant symmetric and asymmetric component values characterizing the cold season. These differences can be attributed to stronger El Niño Modoki episodes and associated atmospheric circulations in the extratropical region during the cold season (Ashok *et al.,* 2007; Yu *et al.,* 2017).

The mechanisms responsible for the symmetric and asymmetric relationships of ENSO and ENSO Modoki episodes to extreme precipitation occurrences in the US were also investigated. It was found that the teleconnections generated by anomalous SSTs associated with the two types of ENSO are consistent with anomalous dynamical and moisture conditions conducive to more occurrences of sub-daily extreme precipitation events in some areas of the US.

Although the results in this study are based solely on composite analyses over a relatively short time period and need to be analyzed further through numerical simulations of the atmospheric dynamics involved in SST-related teleconnections conducive to extreme precipitation in the US, the results do suggest relationships between sub-daily extreme precipitation in the US and episodes of El Niño/La Niña and El Niño Modoki/La Niña Modoki.

Acknowledgements

Supporting information

The following supporting information is available:

Figure S1. Time series of the normalized Niño 3.4 and El Niño Modoki indices for the warm and cold seasons. The dashed lines indicate one standard deviation.

Figure S2. Total number of 1-h extreme precipitation events for the warm and cold seasons during the El Niño and La Niña episodes that occurred from 1979 to 2013.

Figure S3. The standard deviations of the number of 1-h extreme precipitation events that occurred during the warm season El Niño, El Niño Modoki, La Niña, and La Niña Modoki episodes from 1979 to 2013.

Figure S4. The standard deviations of the number of 1-h extreme precipitation events that occurred during the cold season El Niño, El Niño Modoki, La Niña, and La Niña Modoki episodes from 1979 to 2013.

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