A GEFA Assessment of Observed Global Ocean Influence on U.S. Precipitation Variability: Attribution to Regional SST Variability Modes

YAFANG ZHONG

Center for Climate Research, University of Wisconsin—Madison, Madison, Wisconsin, and INSTAAR, University of Colorado, Boulder, Colorado

ZHENGYU LIU AND MICHAEL NOTARO

Center for Climate Research, University of Wisconsin—Madison, Madison, Wisconsin

ABSTRACT

This paper presents a comprehensive assessment of the observed influence of the global ocean on U.S. precipitation variability using the method of Generalized Equilibrium Feedback Assessment (GEFA), which enables an unambiguous attribution of the influence from multiple ocean basins within a unified framework. The GEFA assessment based on observations for 1950–99 suggests that the tropical Pacific SST variability has the greatest consequence for U.S. precipitation, as both ENSO and meridional modes are associated with notable responses in seasonal mean precipitation. The anomalously cold tropical Indian Ocean is a good indicator for U.S. dry conditions during spring and late winter. The impact of North Pacific SST variability is detected in springtime precipitation, yet it is overshadowed by that of the tropical Indo-Pacific on seasonal-to-interannual time scales. Tropical Atlantic forcing of U.S. precipitation appears to be most effective in winter, whereas the northern Atlantic forcing is likely more important during spring and summer.

Global ocean influence on U.S. precipitation is found to be most significant in winter, explaining over 20% of the precipitation variability in the Southwest and southern Great Plains throughout the cold seasons and in the northern Great Plains and northeast United States during late winter. The Southwest and southern Great Plains is likely the region that is most susceptible to oceanic influence, primarily to the forcing of the tropical Indo-Pacific. The Pacific Northwest is among the regions that may experience the least oceanic influence as far as precipitation variability is concerned.

1. Introduction

Numerous papers have been published on oceanic regulation of U.S. precipitation variability, with most of them devoted to providing evidence for one or a couple of ocean–U.S. connections. To evaluate the relative importance and gross impact of the oceanic forcings from multiple basins, one needs to consider them within a unified framework. A recent tendency to employ numerical models (e.g., Hoerling and Kumar 2003; Schubert et al. 2004, 2009; Seager et al. 2007; Shin et al. 2010) in tackling this issue reflects the consensus that climate modeling has the upper hand, as the models yield a dynamically integrated effect given any combination of SST

forcings. However, because of inherent model deficiencies, results often vary considerably among model assessments (e.g., Schubert et al. 2009). Observational assessment, therefore, is vital for evaluating the model performance, but it has been hampered by difficulty with unambiguously accounting for SST forcings that interact with each other in a complex way.

Recently, Liu et al. (2008) developed the Generalized Equilibrium Feedback Assessment (GEFA) method (Liu et al. 2008; Liu and Wen 2008) and demonstrated its ability to exclusively identify the impact of each SST forcing within a unified linear framework. Using the GEFA method, Wen et al. (2010) studied the impacts of global SST variability on geopotential height (GHT) in observations. They showed that the GEFA distinguishes the impact of the North Pacific from that of the tropical Pacific when the interrelated North Pacific and tropical Pacific SST indices are input simultaneously. It further

Corresponding author address: Yafang Zhong, INSTAAR, University of Colorado, 1560 30th St., Boulder, CO 80303.
E-mail: yafang.zhong@colorado.edu

isolates the impact of the tropical Indian Ocean as the correlated tropical Indian SST index is introduced. Thus, the GEFA is able to distinguish the impacts of SST forcings with no need to explicitly filter their interactive effect. In assessing global ocean influence when multiple SST forcings with complex interactions [e.g., Vimont et al. (2001), Alexander et al. (2002), Deser et al. (2004), and Zhong et al. (2008) for interaction of the tropical and North Pacific Oceans; Enfield and Mayer 1997, Giannini et al. (2004), and Guan and Nigam (2008) for Pacific impact on the Atlantic Ocean; Yu and Lau (2004) and Schott et al. (2009) for Pacific impact on the Indian Ocean; and Tourre et al. (1999), Xie and Carton (2004), and Peng et al. (2005) for the interaction of the tropical and North Atlantic Oceans] are under consideration, the GEFA is superior to conventional lagged regression, which requires explicit prefiltering of the interactive effect.

As a follow up to Wen et al. (2010), we use the GEFA to study the influence of global SST variability on U.S. precipitation. This study serves as a first observational assessment of global ocean influence on seasonal-to-interannual U.S. precipitation variability with the hope of providing an observational baseline for comparison with model evaluation. The present work also addresses these pending questions: What is the relative importance of the tropical Atlantic and North Atlantic for U.S. precipitation variability? Is the impact of North Pacific SSTs discernible from that of tropical Pacific SSTs in terms of seasonality and regions affected? Section 2 describes the GEFA method and the observational data used in the study. In section 3, we examine the response patterns of U.S. precipitation to global SST forcings; and in section 4, we evaluate gross oceanic impact on precipitation variability over various U.S. regions. Section 5 contains the summary and further discussions.

2. Data and diagnostic techniques

The data used here are the monthly mean SST, U.S. precipitation, GHT, and wind. The SST, GHT, and wind fields are taken from the National Centers for Environmental Prediction (NCEP) reanalysis on a T62 Gaussian grid (Kalnay et al. 1996). The University of Delaware precipitation data (Willmott and Matsuura 1995) are employed for reasonably good data coverage and quality over the United States for the period 1950–99, which is the time period we focus on herein. The precipitation data are binned into $2.5°$ latitude $\times$ $2.5°$ longitude grids from the original $0.5°$ latitude $\times$ $0.5°$ longitude grids to reduce regional uncertainties. All anomaly fields are obtained by removing the seasonal cycle and then detrended by removing a third-order polynomial fit.

The GEFA is a multivariate generalization of the univariate Equilibrium Feedback Assessment (EFA; Frankignoul et al. 1998; Liu et al. 2006; Notaro et al. 2006a) used to facilitate distinguishing the impacts by interrelated oceanic forcings. A full formulation of GEFA has been demonstrated in Liu et al. (2008) and Liu and Wen (2008), and it is briefly summarized here.

Assume the atmospheric variability, such as precipitation variability $P(t)$, consists of a stochastic part associated with the atmospheric internal variability $N(t)$ and a SST-forced part $B \times S(t)$, such that

$$P(t) = B \times S(t) + N(t). \tag{1}$$

The SST field $S(t)$ consists of J points, representing J SST indices. Here, B is the response sensitivity matrix with components b_j measuring the impact of the jth SST index on the precipitation field. Contemporaneous association of extratropical SSTs and atmospheric variability primarily reflects the atmosphere driving the ocean, requiring that calculations aimed at quantifying oceanic feedbacks to the atmosphere use data with the atmosphere lagging the ocean (Frankignoul et al. 1998; Czaja and Frankignoul 2002). Therefore, B is derived with atmosphere-lagged covariances as

$$B(\tau) = C_{PS}(\tau)C_{SS}^{-1}(\tau), \tag{2}$$

where τ is a SST lead time that is longer than the damping time scale of the atmosphere, $C_{PS}(\tau)$ is the lagged cross-covariance matrix between precipitation and SST, and $C_{SS}(\tau)$ is the autocovariance matrix of SST. Discrimination of the impacts by interrelated SST forcings now becomes effortless by singling out each component b_j. Here, τ is chosen to be 1 month in this study, as $\tau = 2$ months tends to yield similar results.

The GEFA response has been related to the EFA response (Liu et al. 2008; Liu and Wen 2008) as

$$A = B \times M, \tag{3}$$

where A is the EFA response sensitivity matrix with components

$$a_j \equiv \frac{C_{PS_j}(\tau)}{C_{s_j s_j}(\tau)} \tag{4}$$

measuring the impact of the jth SST index on precipitation using the univariate EFA as if the response was forced entirely by the jth SST, and M is a forcing matrix with elements

$$m_{ij} \equiv \frac{C_{s_i s_j}(\tau)}{C_{s_j s_j}(\tau)} \tag{5}$$

reflecting the covariance among SST forcings. The interpretation of (3) is that the EFA response to the jth SST forcing a_j is the sum of the contributions from all the SST forcings, with each contribution being the GEFA response b_i weighted by m_{ij} (Wen et al. 2010).

In principle, the GEFA can be performed using various forms of SST forcings as long as they are spatially orthogonal. However, it may suffer from a significant sampling error when SST forcings are highly correlated, and thus $C_{SS}(\tau)$ is ill conditioned, as in the case of gridded SSTs with high spatial resolution. A test with a simple model has shown that the GEFA using SST modes from regular EOF analysis has substantially less sampling error in estimating the feedback matrix B than using original gridded SSTs (L. Fan et al. 2010, unpublished manuscript).

Because of our intention to discriminate the effects of different ocean basins, and the importance of different combinations of SST anomalies for U.S. precipitation variability (Hoerling and Kumar 2003; Schubert et al. 2009; Shin et al. 2010), we use regional SST modes, rather than global modes, as the forcing input of (1) and (2). Here, SST modes from regular EOF, rather than those from rotated EOF analysis, are elected since the former are usually those that are the definition of classic SST variability modes, for example, ENSO and the Pacific decadal oscillation (PDO; Mantua and Hare 2002). Nevertheless, it could be interesting to examine the impact of localized SST variability by performing GEFA with rotated EOF modes (Davis 1984; Mestas-Nunez 2000) as the base, as in Zhong and Liu (2008).

Following Wen et al. (2010), the SST indices are the time coefficients associated with the leading EOF modes in each of these five ocean basins: the tropical Pacific (TP; 20°S–20°N, 100°E–80°W), North Pacific (NP; 20°–60°N, 120°E–80°W), North Atlantic (NA; 20°–60°N, 70°W–20°E), tropical Atlantic (TA; 20°S–20°N, 70°W–20°E), and tropical Indian Ocean (TI; 20°S–20°N, 35°–120°E). For most basins, the first two leading SST modes stand out from background noise and have a relatively clear physical meaning. So the first two modes are used from each basin, resulting in 10 SST indices. Wen et al. (2010) studied the sensitivity of the GEFA response to the choice in EOF truncation and concluded that the GEFA response is reasonably stable. Indeed, we found that adding the third EOF mode produces largely consistent results. To test the sensitivity to location and size of the EOF domains for the ocean basins, we repeat the analyses but change the EOF domains to the following: (i) TP (25°S–25°N, 110°E–80°W), NP (15°–65°N, 110°E–110°W), NA (15°–65°N, 80°W–0°), TA (25°S–25°N, 80°W–0°) and TI (25°S–25°N, 40°–110°E); and (ii) TP (15°S–15°N, 100°E–90°W), NP (25°–60°N, 100°E–120°W), NA (25°–60°N, 90°–10°W), TA (15°S–15°N,

60°W–10°E), and TI (15°S–15°N, 50°–100°E). It suggests the GEFA results are fairly insensitive to the location and size of the EOF domains for the ocean basins. Moreover, the results have been essentially reproduced using data for the subperiod 1960–99.

For seasonal mean response, 3-month-averaged SSTs are used in the EOF analysis yielding the SST spatial patterns, on which the original monthly SSTs are projected to derive the corresponding monthly resolved time coefficients. The covariance matrices C_{PS} and C_{SS} are then estimated for each calendar month and next averaged over the season. Here, late winter is defined as January–March (JFM), spring as April–June (AMJ), summer as July–September (JAS), and early winter as October–December (OND). Seasonal mean response is finally calculated by (2) using the averaged covariance. For example, the procedure to derive OND precipitation response is as follows: (i) perform EOF analysis for each basin with OND-averaged SSTs; (ii) derive the 10 SST time coefficients by projecting monthly SSTs onto the spatial patterns resulted from (i); (iii) estimate October C_{PS} with October precipitation and September SST time coefficients, November C_{PS} with November precipitation and October SST, and December C_{PS} with December precipitation and November SST; (iv) calculate OND C_{PS} as the average of October, November, and December C_{PS}; (v) estimate OND C_{SS} similarly to OND C_{PS}; (vi) obtain OND precipitation response sensitivity B by dividing OND C_{PS} by OND C_{SS}; and, finally, (vii) multiply OND precipitation response sensitivity by OND SST standard deviation to get OND precipitation response.

A significance test of B is performed using the Monte Carlo bootstrap approach (Czaja and Frankignoul 2002). The computation of B is repeated 5000 times, each using randomly scrambled atmospheric time series. Note that atmospheric seasonality is retained, as only the order of the years is changed, not that of the months. Based on the produced accumulative probability, we determine the significance for each element of B (or grid cell) and for the percentage of B elements that are significant at the 90% confidence level, that is, the field significance of B. All precipitation response fields shown here are significant at the 90% confidence level. To help interpret the SST–U.S. linkages, we also calculate the responses in GHT and wind for a dynamic context. Noteworthy is that the GEFA results only provide statistical associations among the fields, not the dynamic causality. Because of the linear nature of the GEFA method, a discussion of the ocean–U.S. connection below applies for both polarities—that is, the reversed phase of the SST mode is associated with the same atmospheric response but with an opposite sign.

3. U.S. precipitation response patterns to SST mode forcings

In this section, we examine the observed U.S. precipitation response to SST variability in each of the five ocean basins using the GEFA. To ease the burden of figures, we only show spatial patterns from EOF analyses of monthly SSTs (Fig. 1), as we have noted a large resemblance in the monthly pattern for all the seasonal SST forcings discussed below. Our discussion starts with the forcing of the tropical Pacific given that its impact is the most understood to date.

a. Tropical Pacific teleconnective forcing

1) ENSO MODE

The leading EOF pattern of tropical Pacific SST (TP1; Fig. 1a) is the classic ENSO mode explaining 58% of the total monthly variance. It is generally accepted as being self generated in the tropical Pacific Ocean–atmosphere coupled system (Anderson et al. 1998) and of a worldwide climate consequence through atmospheric teleconnection (Alexander et al. 2002). The ENSO impacts U.S. precipitation during its summer growing season and early winter maturing season by sending out Rossby wavetrains and hence altering the atmospheric circulation (Seager et al. 2005a,b). In summer, Rossby wavetrains are established with an anomalous high sitting over northern North America (Fig. 2a) as a response to the cold phase of ENSO or La Niña events. The associated weaker westerly jet over the northern United States is adverse to storm activity, resulting in an overall dry condition in the northern tier of the United States from the Pacific Northwest (PNW) to the Great Lakes (Fig. 2b). The precipitation deficit is largest in the northern Midwest (MW; over 1 cm month^{-1}), probably because of the additional drying effect of the decreased northward moisture transport associated with the weakened Great Plains low-level jet (GPLLJ) (Fig. 2a), whereas in the Atlantic coastal area increased precipitation may result from enhanced moisture transport from the ocean (Fig. 2b). Our GEFA essentially reproduces the summertime pattern of ENSO-induced precipitation as demonstrated by Ting and Wang (1997) using lagged singular value decomposition (SVD) analysis.

In early winter, La Niña events likely excite equivalent barotropic wavetrains over the Pacific and North America (Fig. 2c). Accordingly, the jet stream is displaced northward over the central United States, disfavoring synoptic storms and thus precipitation over the Southwest and Great Plains (Fig. 2d).

Overall, our assessment of the impacts by Pacific ENSO mode is qualitatively consistent with previous ENSO studies in the sense that the induced precipitation anomalies are concentrated over the Southwest, the Great Plains, and the southernmost tier of the United States in early winter (Ropelewski and Halpert 1996), and over the northern United States and Atlantic coastal area in summer (Mo et al. 2009).

2) TROPICAL PACIFIC MERIDIONAL MODE

Explaining 12% of the monthly variance, the second EOF mode of the tropical Pacific SSTs (TP2; Fig. 1b) resembles the Pacific meridional mode (PMM; Chiang and Vimont 2004) showing a thermal contrast between the northern tropical Pacific and eastern equatorial Pacific. It is potentially maintained by a positive feedback between surface winds, evaporation, and SST (WES) feedback (Xie and Philander 1994; Chiang and Vimont 2004). In the phase of positive meridional thermal gradient, the tropical Pacific meridional mode (TPM) tends to be associated with dry spells in a large area of the northern United States from the Great Plains to the northeast (NE) United States during late winter (Fig. 3b), possibly through a negative North Atlantic Oscillation (NAO)–like change and the associated amplified wave pattern of the North American jet (Dai et al. 1997; Enfield et al. 2001; Notaro et al. 2006b) (Fig. 3a). The northerly anomalies across the eastern United States are conducive to the intrusion of dry continent air from Canada, which disfavors precipitation in the eastern United States, northern Great Plains (NGP), and the Midwest. In summer, the TPM is associated with an anomalous low over northern North America and an anomalous high over the eastern United States (Fig. 3c), which indicates an intensified North American jet and a strengthened GPLLJ. Increased synoptic storms and enhanced moisture transport from the south could be expected to produce copious precipitation over the U.S. Midwest (Fig. 3d).

Compared to the ENSO mode, the impact of TPM is found in different U.S. regions during winter, whereas both modes may affect the northern Midwest in summer. Hence, the summertime ENSO effect could be magnified or reduced depending on the phase of TPM.

b. North Pacific downstream forcing

The North Pacific has been suggested to affect the U.S. precipitation by modulating the Pacific storm track activity that is intimately connected to U.S. precipitation (Ting and Wang 1997; Barlow et al. 2001; Castro et al. 2001). Here, the impact of leading North Pacific modes is evident over some U.S. regions but not so for the whole United States (not shown), as determined by the field significance test.
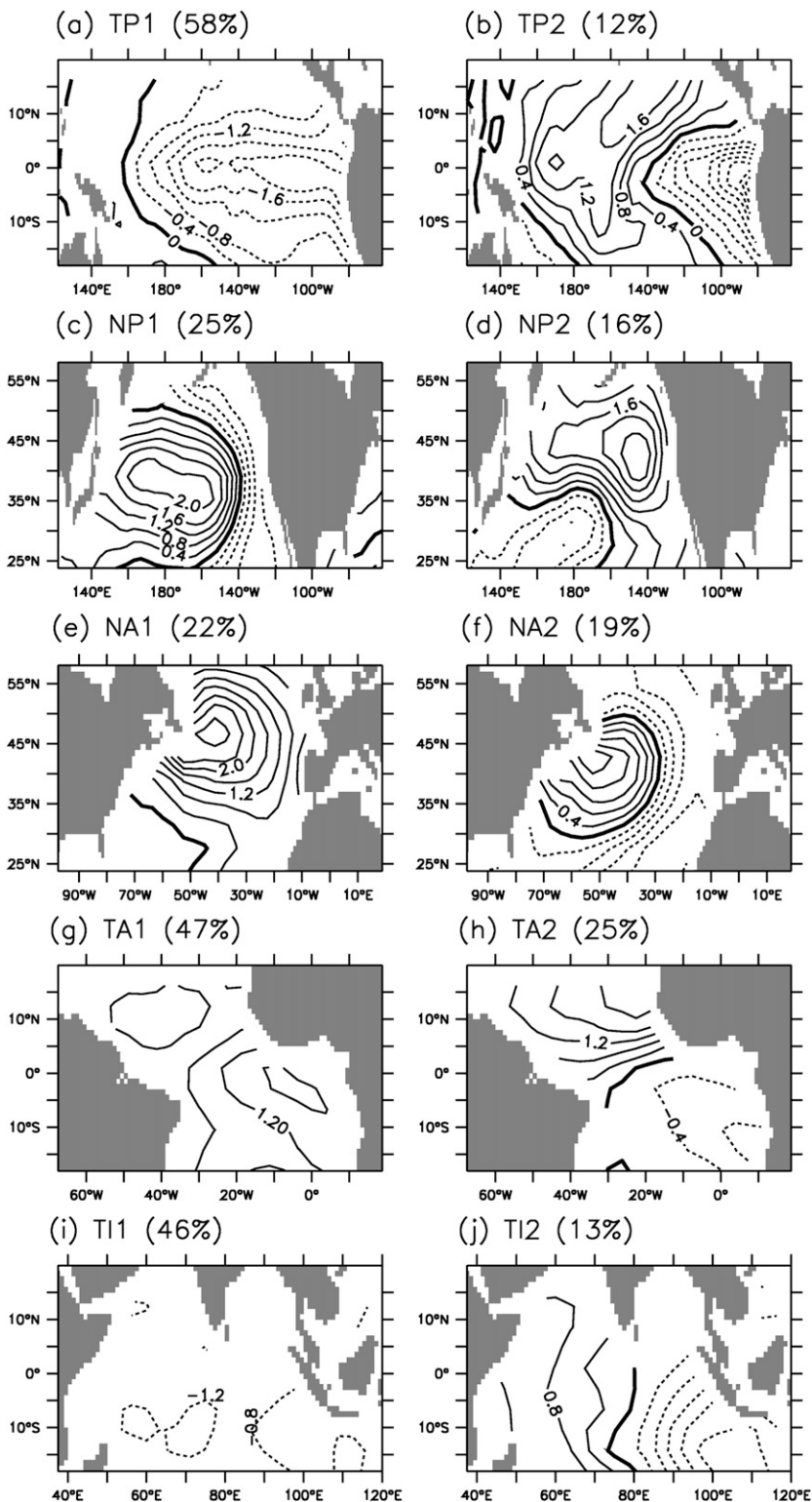
FIG. 1. The first two leading SST modes from each of the five ocean basins: TP, NP, NA, TA, and TI. The SST modes are as follows: (a) tropical Pacific ENSO TP1 and (b) meridional TP2 modes; (c) Pacific decadal oscillation (NP1) and (d) North Pacific meridional mode (NP2), (e) North Atlantic monopole (NA1) and (f) tripole (NA2) modes; (g) tropical Atlantic Niño (TA1) and (h) meridional (TA2) modes; and the (i) tropical Indian Basin (TI1) and (j) dipole (TI2) modes. Explained fractions of monthly variance are given in parentheses. Contour interval (CI) = 0.4°C.
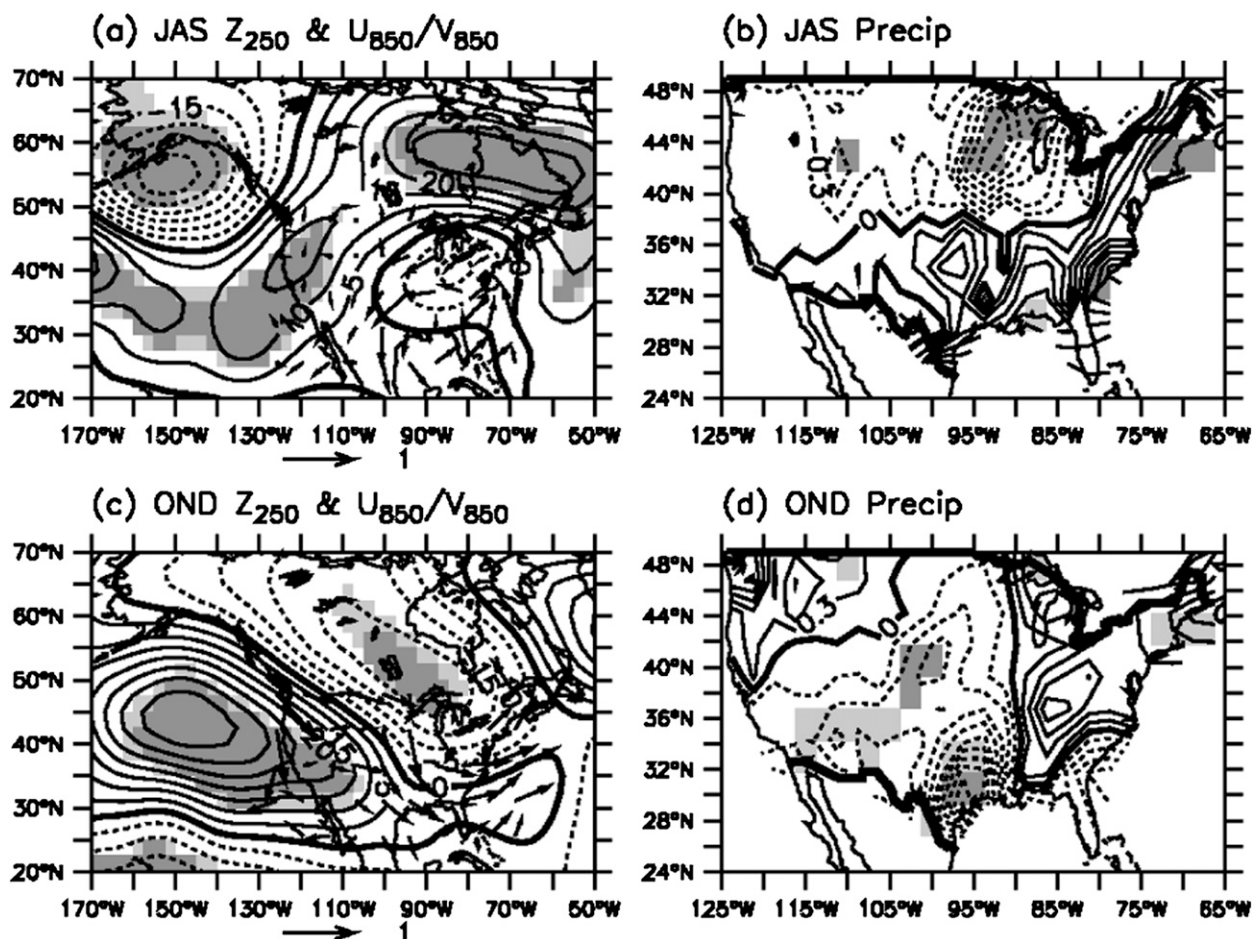
FIG. 2. (a),(b) JAS and (c),(d) OND responses of geopotential height at 250 hPa (CI = 5 m per std dev of SST; contour) and wind at 850 hPa (unit vector = 1 m s^{-1} per std dev of SST) and U.S. precipitation (CI = 0.3 cm month^{-1} per std dev of SST) to the forcing of first SST EOF in the tropical Pacific, that is, the ENSO mode (Fig. 1a). Dark- and light-gray shading indicates geopotential height and precipitation responses that are significant at the 90% and 85% confidence levels, respectively.

c. Atlantic forcing: North Atlantic and tropical Atlantic

The Atlantic SSTs influence conterminous continents, in particular, North America and Europe (Enfield et al. 2001; Sutton and Hodson 2005; Wang et al. 2006, 2007; Schubert et al. 2009; Weaver et al. 2009). The tropical Atlantic is generally regarded as a more plausible source than the North Atlantic for U.S. precipitation variability (Cook et al. 2007), in that tropical SST anomalies are usually more effective at inducing changes in large-scale atmospheric circulation, from both theoretical (Hoskins and Karoly 1981) and numerical experimental viewpoints (Kushnir et al. 2002). However, there is building evidence for extratropical ocean feedbacks to the atmosphere (Czaja and Frankignoul 2002; Liu and Wu 2004; Frankignoul and Sennechael 2007; Liu et al. 2007; Zhong and Liu 2008), hinting at a possible role of the

North Atlantic Ocean in generating U.S. precipitation variability. Of specific interest in this subsection is the relative importance of the tropical Atlantic and North Atlantic forcing.

1) NORTH ATLANTIC TRIPLE MODE

The tripole mode is the second leading EOF of monthly North Atlantic SSTs (NA2; Fig. 1f), explaining 19% of the total variance. It arises primarily as a result of the NAO forcing, with a one-sign anomaly in the western central North Atlantic and an opposite sign to the Northeast and Southeast (SE; Wallace et al. 1990). The North Atlantic triple mode (NAT) appears to promote precipitation in spring over the northeast United States (Fig. 4b), likely with the help of low-level southwesterly anomalies across the eastern United States (Fig. 4a) that transport moisture from the south. The NAT is able to feedback to the atmosphere by generating a positive NAO-like response
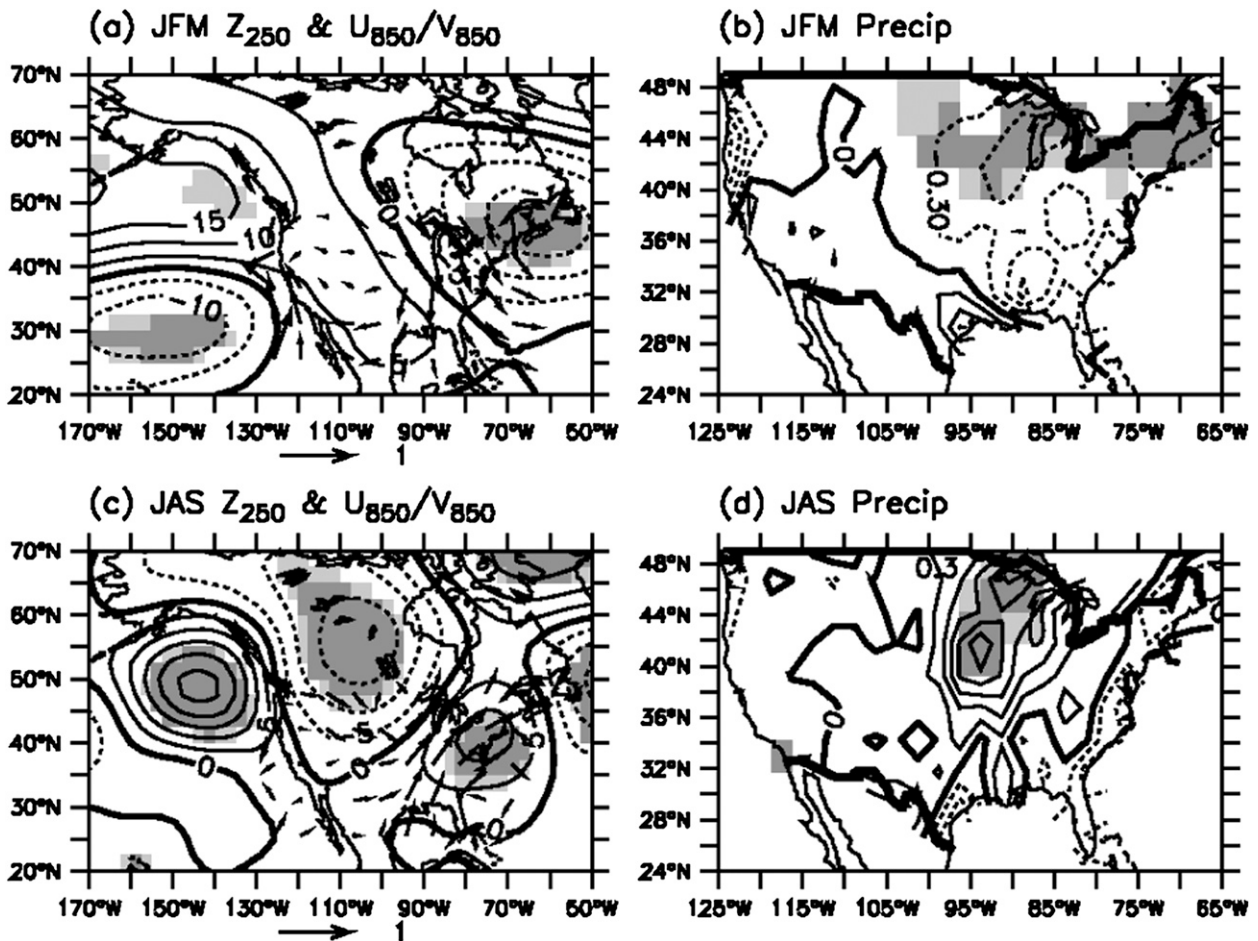
FIG. 3. As in Fig. 2, but for JFM and JAS responses to the forcing of the second SST EOF in the tropical Pacific, that is, the tropical Pacific meridional mode (Fig. 1b).

in early winter (Czaja and Frankignoul 2002), but it has no significant effect on U.S. precipitation (not shown). As previous studies (Dai et al. 1997; Notaro et al. 2006b) have shown the associations between NAO and precipitation variability in the eastern United States during fall and winter, our result implies the importance of structural details of a NAO-like change for U.S. precipitation response.

2) TROPICAL ATLANTIC MERIDIONAL MODE

The tropical Atlantic meridional mode (TAM) is the second leading EOF of tropical Atlantic SSTs (TA2; Fig. 1h) and has a dipolar structure with predominant loadings in the northern tropical Atlantic (Chang et al. 1997; Xie 1999; Xie and Carton 2004), explaining 25% of the total monthly variance. Like the TPM, it could be maintained by the WES feedback. The GHT responses in early winter are barotropic, characterized by a zonal dipole pattern over the North America (Fig. 5a), indicating an amplified ridge–trough pattern that may facilitate the

intrusion of the Canadian continental dry air into the central United States and thus result in an anomalously dry condition (Fig. 5b). The anomalous high over western North America (Fig. 5a) is associated with a weaker westerly jet over the southwestern United States and hence is adverse to storm activity and precipitation (Fig. 5b).

The U.S. precipitation response to tropical Atlantic SSTs has more distinctive geographic features and seasonality than that of northern Atlantic SSTs. The tropical Atlantic forcing appears to be most effective in winter, whereas the northern Atlantic forcing is more important in warmer seasons.

d. Remote forcing of tropical Indian Ocean

While the tropical Indian Ocean is long recognized as influencing precipitation variability over the adjacent land area, its far-reaching impact has not been widely studied until the finding of Hoerling et al. (2001) on a potential linkage to the NAO. Recently, Wen et al.
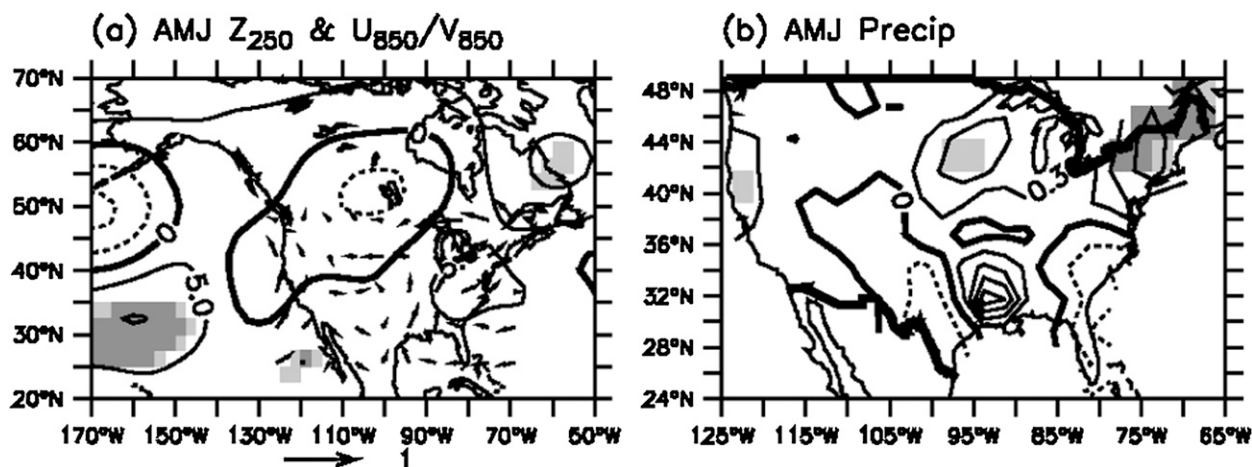
FIG. 4. AMJ responses of (a) geopotential height at 250 hPa (CI = 5 m per std dev SST; contour) and wind at 850 hPa (unit vector = 1 m s^{-1} per std dev SST), and (b) U.S. precipitation (CI = 0.3 cm month^{-1} per std dev of SST) to the forcing of second SST EOF in the North Atlantic, that is, the North Atlantic tripole mode (Fig. 1f). Dark- and light-gray shading indicates geopotential height and precipitation responses that are significant at the 90% and 85% confidence levels, respectively.

(2010) suggested that the tropical Indian Ocean might be as effective as the tropical Pacific at inducing changes in the global atmospheric circulation. Modeling studies by Schubert et al. (2004) and Wu and Kinter (2008) further argued that the tropical Indian SSTs have substantial impact on medium and long-term U.S. dry conditions. Here, we investigate the role of the tropical Indian Ocean at influencing U.S. precipitation variability.

The tropical Indian Basin mode (TIB; Schott et al. 2009) is the first leading EOF of tropical Indian SSTs (TI1; Fig. 1i), explaining 46% of the total monthly variance. It arises mainly from changes in surface heat fluxes associated with Pacific ENSO variability (Wallace et al. 1998; Venzke et al. 2000). Lagging Pacific ENSO by a season, it tends to peak in late winter and persist

into spring (Deser et al. 2010). It has been suggested that SST variability in the tropical Indo-Pacific could excite circumglobal wavetrains in the extratropics (Branstator 2002). Here, the TIB is associated with an anomalous low and northeasterly anomalies over the eastern United States in spring (Fig. 6a), which indicates weaker GPLLJ and decreased moisture transport from the Gulf of Mexico in favor of a precipitation deficit in the northwest, southeast, and northeast United States (Fig. 6b). As a concomitant mode, the TIB could extend the ENSO's influence into spring.

For the United States as a whole, the tropical Pacific SSTs seem to have the greatest consequence, agreeing with Cook et al. (2007). For regional precipitation, the relative importance of SST forcings may be different
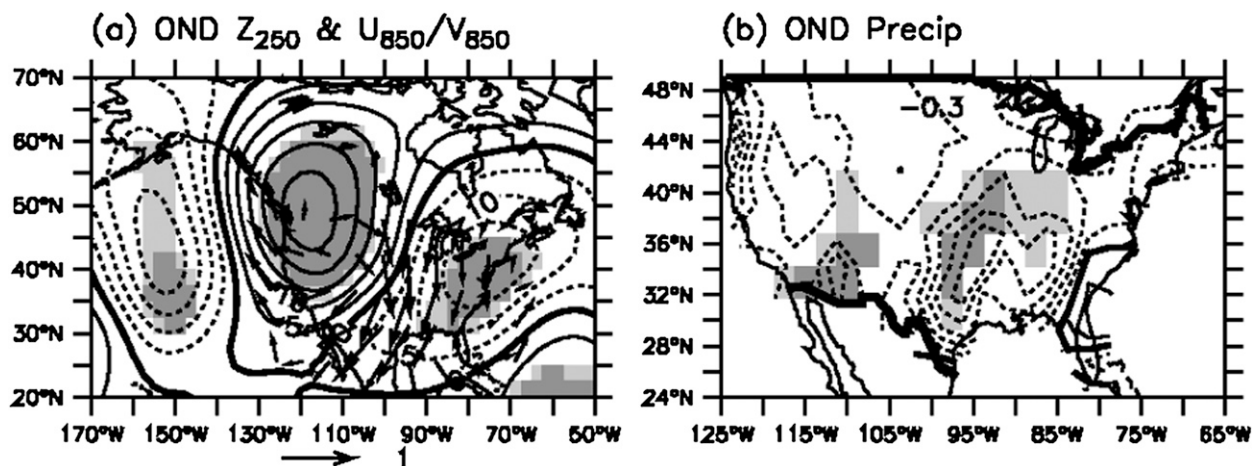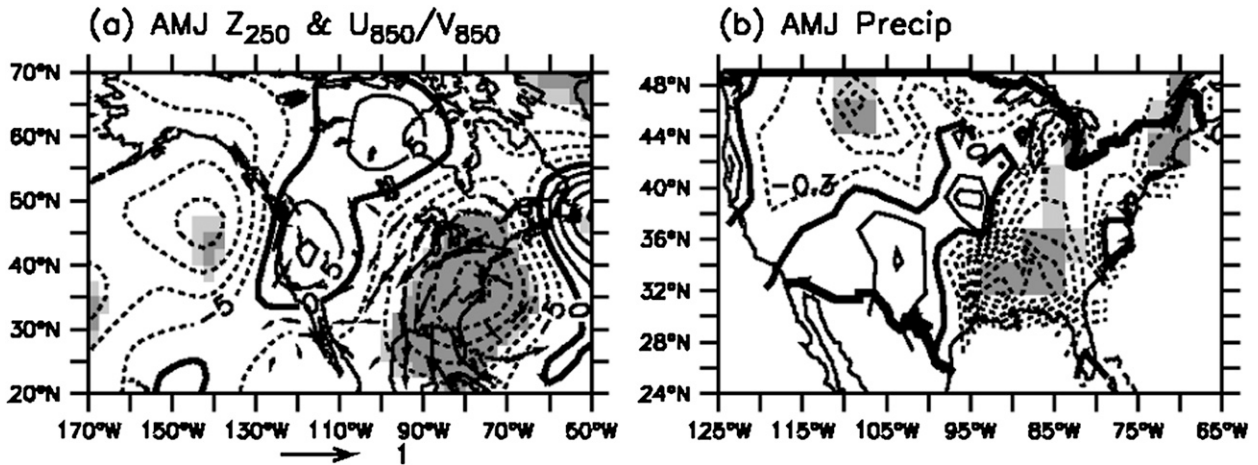

FIG. 5. As in Fig. 4, but for OND responses to the forcing of the second SST EOF in the tropical Atlantic, that is, the tropical Atlantic meridional mode (Fig. 1h).
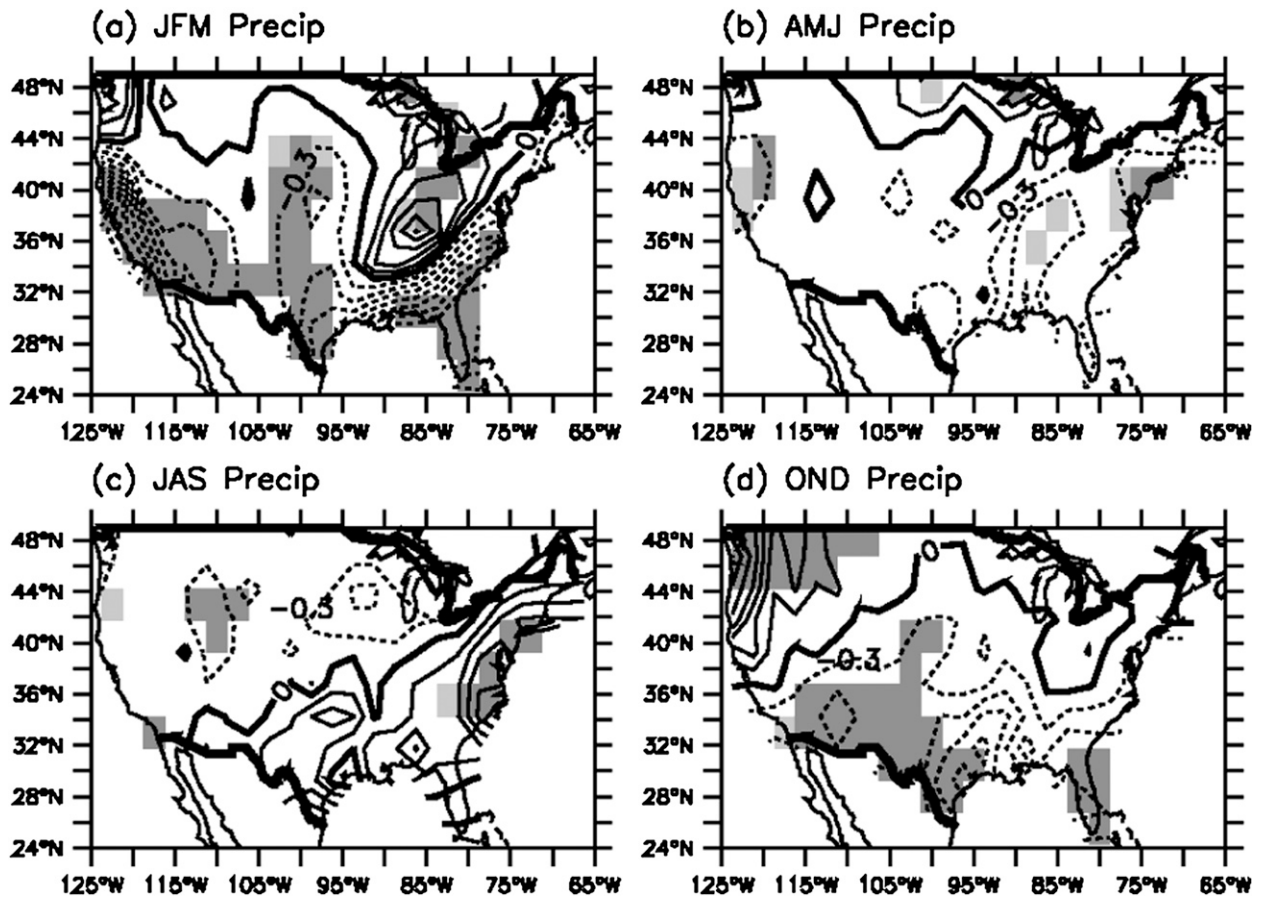
FIG. 6. As in Fig. 4, but for AMJ responses to the forcing of the first SST EOF in the tropical Indian Ocean, that is, the tropical Indian basin mode (Fig. 1i).

and seasonally dependent. In the following section, we proceed to examine the ocean–U.S. connection but from an alternative perspective of U.S. regional precipitation.

4. SST forcings for U.S. regional precipitation

We examine the SST mode forcings on seasonal mean precipitation in six U.S. regions: the Southwest and southern Great Plains (SWSGP), Pacific Northwest, northern Great Plains, Midwest, Northeast, and Southeast (Fig. 7). As for the U.S. response, we conduct a field significance test for the regional response, that is, a subset of B. To get the overall precipitation response in each region, we repeat the calculation of (1) and (2) but using the six time series of regionally averaged precipitation for the atmospheric field. The newly derived regional response is also subject to a statistical significance test using the Monte Carlo bootstrap approach. The regional response, or the corresponding SST forcing, is declared as significant only if this test and the field significance test both indicate so. The response is in close proximity with that obtained by simply averaging over each region the gridded response as shown in Figs. 2–6, attesting to the

FIG. 7. Schematics of the six U.S. regions: SWSGP, PNW, NGP, MW, NE, and SE. Monthly climatology of the regionally averaged precipitation (cm month^{-1}) is shown in the bar charts.

FIG. 8. The EFA responses of (a) JFM, (b) AMJ, (c) JAS, and (d) OND U.S. precipitation (CI = 0.3 cm month^{-1} per std dev SST) to the forcing of Pacific ENSO mode (Fig. 1a). Dark- and light-gray shading indicates responses that are significant at the 90% and 85% confidence levels, respectively.

robustness of our assessment. We further reconstruct the seasonal mean time series of regionally averaged precipitation $P_r(t)$ using those significant SST forcings only, such that

$$P_r(t) = B_c \times S_m(t), \quad (6)$$

where B_c is same as B but with those insignificant response coefficients replaced with zeros, and $S_m(t)$ is the six time series of regionally averaged seasonal SST. To quantify the gross oceanic impact on seasonal mean precipitation, we perform linear correlation of the re-constructed and actual time series, and the square of correlation coefficient gives the fraction of precipitation variability that may be oceanically induced. Among those significant SST forcings, the one with the largest response can be viewed as having the largest impact on the regional precipitation.

To facilitate the comparison with previous studies on ENSO impact, we show in Fig. 8 the EFA response to

the Pacific ENSO mode, which can be derived by Eq. (4) or using Eq. (2) but with a sole SST index—the ENSO mode in this case. It is mathematically equivalent to the response obtained by the atmosphere-lagged regression with the damping of SSTs taken into account (Zhong and Liu 2009), and it largely captures the features of ENSO impacts revealed by previous studies. Physically, the EFA response to the Pacific ENSO mode can be interpreted as a mixture of responses to global SST anomalies that are associated with the ENSO, whereas the GEFA is a decomposition of the EFA response (Liu et al. 2008).

a. SWGSP

The Southwest and southern Great Plains is likely the region that is most susceptible to oceanic influence, with over 20% of wintertime precipitation variance attrib-utable to SST forcing (Table 1). The major SST forcing appears associated with the ENSO cycle, consistent with the notion that La Niña produces dry winters in the

TABLE 1. Response of seasonal mean precipitation (cm month^{-1} per std dev SST) over the Southwest and SWSGP to the two leading SST modes from each of the five ocean basins: TP, NP, NA, TA, and TI. The SST modes are as follows: TP1 and TP2 modes; NP1 and NP2; NA1 and NA2 modes; TA1 and TA2 modes; and TI1 and TI2 modes. Responses significant at the 90% confidence level are highlighted in bold. The last column gives oceanic-induced fractions (%) of precipitation variance (cm month^{-1}). Note that no value is given for JFM NP2, JFM, or JAS TI2, as the North Pacific meridional mode or tropical Indian dipole mode is not in the top two EOFs during those seasons. The SST modes with no significant precipitation response are not shown here.

SWSGP	TP1	TA1	TA2	TI1	%
JFM	−0.09	**−0.27**	−0.18	**−0.52**	25
AMJ	−0.26	−0.08	−0.17	−0.10	0
JAS	0.08	−0.13	−0.22	−0.19	0
OND	**−0.53**	−0.17	**−0.39**	0.09	24

southwest United States and the Great Plains (Ropelewski and Halpert 1986; Andrade and Sellers 1988; Gutzler et al. 2002; Sheppard et al. 2002; Mo et al. 2009). Our GEFA results further suggest that the major forcing is delivered by Pacific SSTs in early winter and relayed by tropical Indian SSTs, with tropical Atlantic SSTs playing a minor role. It agrees with the finding of Cayan et al. (1998) that the precipitation variability over the Southwest is connected to global tropical SST forcing in all three basins. The oceanic influence is less appreciable in spring and summer, when local land processes probably dominate the precipitation variability (Hu and Feng 2002).

b. PNW

The PNW is one of the regions that may experience the least oceanic influence, with the largest (13%) precipitation variability explained by SST forcing in spring (Table 2). The wetter-than-average springs are associated with warm anomalies in the tropical Indian Ocean and/or the negative phase of North Pacific meridional mode (Bond et al. 2003; Lau et al. 2004), that is, a relaxed meridional thermal gradient in the western North Pacific (Fig. 1d). Cayan et al. (1998) also found the "Northwest" precipitation mode is affected by SST anomalies in the tropical Indian Ocean and North Pacific but with a reversed sign or different spatial pattern. Inspection of their precipitation patterns, however, suggests that the "Wyoming" precipitation mode, rather than the Northwest mode, better matches with our PNW pattern, as in Fig. 6b.

It has been suggested that La Niña favors wet winters in the PNW (Ropelewski and Halpert 1986; Mote et al. 2003), which is evident in the EFA response to the ENSO (Fig. 8d) but insignificant in our GEFA response (Fig. 2d). The reason could be that the anomalously wet

TABLE 2. As in Table 1, but for responses over PNW.

PNW	NP2	NA1	TI1	%
JFM	N/A	−0.15	0.39	0
AMJ	**0.28**	0.17	**−0.46**	13
JAS	−0.04	−0.03	0.10	0
OND	0.10	**0.35**	−0.23	6

conditions result from the combined effects of tropical and North Pacific SST anomalies associated with the ENSO events, and that either effect alone is indistinguishable from background noise. It holds true for additional GEFA calculation using only the ENSO and PDO (Fig. 1c) as input SST indices (not shown). A hint is that our GEFA assessment likely underestimates the oceanic-induced fraction of precipitation variability since it does not account for the combined effects of insignificant SST forcings.

c. NGP

The NGP is subject to oceanic influence during the winter half-year, especially in late winter when 20% of precipitation variability is associated with the tropical Pacific meridional mode and Atlantic Niño mode (Table 3). No significant ENSO impact is detected in warm wet seasons, disagreeing with Ting and Wang (1997) and Bunkers et al. (1996), who both argue that El Niño produces abundant summertime precipitation. Noticeably, this summertime ENSO impact is also absent in the EFA response (Fig. 8c).

d. MW

Oceanic impact on MW precipitation appears to maximize in late winter and summer, explaining about 15% of the total variance (Table 4). The tropical Pacific leads the SST forcing, with a minor role in the North Atlantic. It is consistent with Booth et al. (2006) and White et al. (2008), who showed that the MW precipitation is affected by tropical Pacific and North Atlantic SSTs.

e. NE

The NE is most likely affected by SST forcing during late winter and spring, when 13%–25% of the total precipitation variance may be oceanically induced (Table 5). The late winter dry spells could be linked to the tropical Pacific meridional mode through a negative NAO-like

TABLE 3. As in Table 1, but for responses over NGP.

NGP	TP2	NA2	TA1	TI2	%
JFM	**−0.24**	0.12	**0.21**	N/A	20
AMJ	−0.09	0.31	0.03	0.00	0
JAS	0.32	**0.39**	0.33	N/A	0
OND	−0.09	0.05	−0.05	**−0.36**	8

TABLE 4. As in Table 1, but for responses over the MW United States.

MW	TP1	TP2	NP1	NA2	TI2	%
JFM	0.36	**−0.51**	−0.04	−0.01	N/A	15
AMJ	**0.68**	−0.38	**−0.48**	**0.41**	**0.48**	8
JAS	**−0.88**	**0.89**	0.15	**0.53**	N/A	14
OND	0.34	0.20	−0.03	0.24	−0.27	0

TABLE 5. As in Table 1, but for responses over the NE United States.

NE	TP1	TP2	NA2	TI1	%
JFM	−0.04	**−0.23**	0.01	0.16	25
AMJ	0.23	−0.12	**0.26**	**−0.30**	13
JAS	0.10	0.04	0.12	−0.02	0
OND	**0.25**	0.06	0.15	**−0.24**	3

change, whereas the springtime dry condition is associated with cold anomalies in the tropical Indian Ocean and/or the western central North Atlantic. The Pacific ENSO mode seems to have little impact on the NE precipitation during late winter, differing from the finding of Griffiths and Bradley (2007) that La Niña favors below-average consecutive dry days. Instead, La Niña is found to promote precipitation in early winter yet contribute little to the total variance, which is possibly due to the counteractive drying effect of a cold tropical Indian Ocean.

f. SE

Oceanic influence on SE precipitation is most evident in spring, when SST anomalies in the tropical Indian Ocean likely produce 16% of the total variance with the aid of Pacific SST anomalies. The influence of the Pacific ENSO mode is small on the regionally averaged precipitation. Previous studies suggested that La Niña favors the wintertime dry condition in the southernmost SE and a wetter-than-average summer in the Atlantic coastal area (Ropelewski and Halpert 1986; Montroy 1997; Roswintiarti et al. 1998), which is confirmed by the EFA response in Fig. 8. However, these ENSO effects are not as significant in our GEFA response (Fig. 2), indicating a possible underestimation of oceanic-induced precipitation variability here. Combined with the neglect of additive effects by insignificant SST forcings, and that higher-order SST variability modes may also impact U.S. precipitation, it suggests that our GEFA assessment might in effect obtain a lower bound for the oceanic-induced fraction of U.S. precipitation variability.

All the precipitation responses shown in Tables 1–6 are derived by Eqs. (1) and (2), with $\tau = 1$ month for SST leading time. The adoption of $\tau = 2$ months yields generally consistent estimation for the 27 significant responses, as all but one of these responses maintains the same sign irrespective of τ. For 22 (24) out of the 27 responses, the response magnitude derived with $\tau = 2$ months falls within a range of 0.5–2 (0.4–2.5) times of that with $\tau = 1$ month. Using the modified SST EOF domains or data of the subperiod 1960–99 yields a response magnitude within 0.5–2 (0.4–2.5) times of those shown here for 26 (27) out of the 27 responses, while all maintaining a same sign. The reasonably stable results

are rather encouraging for our effort to assess the global oceanic impact, given the high noise level of land precipitation variability, that is, the general governance by internal atmospheric variability.

5. Summary and discussions

To illuminate global oceanic influence on the U.S. precipitation variability, we examine the response patterns of U.S. precipitation to the leading EOF modes of regional SSTs within a unified framework. Our assessment unveils new features of global ocean–U.S. linkages while confirming some previously established key components. The Pacific ENSO influence is notable over the northern United States in summer and over the Southwest and Great Plains in early winter, in accordance with previous knowledge. In addition to these direct impacts, the ENSO may exert a secondary influence as the ensuing tropical Indian SST anomalies tend to be associated with significant precipitation response over the southwest United States in late winter and the Pacific Northwest and eastern United States in spring.

The TPM is shown for the first time to have a significant impact on U.S. precipitation. With warm SST anomalies in the northern tropical Pacific and cold anomalies in the eastern equatorial Pacific, the TPM may be connected to dry conditions in the northern tier of the United States from the Great Plains to the Northeast during late winter. The TPM effect is also observed in summertime precipitation, as evidenced by the wet anomalies concentrated in the U.S. Midwest.

The North Pacific SST variability is associated with a springtime precipitation response over the Northwest, Midwest, and Southwest; however, the response magnitudes are dwarfed by those associated with the tropical

TABLE 6. As in Table 1, but for responses over the SE United States.

SE	TP2	NP2	TI1	%
JFM	−0.10	N/A	0.03	0
AMJ	**−0.17**	**0.19**	**−0.33**	16
JAS	0.04	0.11	0.01	0
OND	−0.07	0.15	−0.16	0

Indo-Pacific forcing. This assessment is in line with Cook et al. (2007), but it disagrees with Wang and Ting (2000), who found North Pacific SSTs more important for U.S. precipitation variability.

Insights have also been achieved regarding potential Atlantic forcing on U.S. precipitation variability. The tropical Atlantic forcing appears to be most effective in winter, with the TAM favoring dry conditions over the Southwest and Great Plains in its positive phase (with positive meridional gradient). The northern Atlantic forcing is likely more important in warmer seasons with the NAT's contribution to the Midwest and Northeast precipitation variability.

Of the six U.S. regions, the SWSGP and Northeast are likely the most influenced by SST forcing, whereas the Northwest and Southeast may be the least affected. The global ocean explains over 20% of the precipitation variability in the SWSGP throughout the cold seasons and in the northern Great Plains and Northeast during late winter. It indicates that oceanic forcing on U.S. precipitation is most important in winter. Our assessment of global ocean–U.S. linkages provides an observational benchmark for the calibration of model performance. To reproduce the ocean–U.S. linkages, the models are required to realistically simulate both global SST variability and the concomitant impacts on U.S. precipitation. The utility of the GEFA in distilling the significant SST forcings poses it as a plausible statistical tool for forecasting U.S. precipitation, which is a subject of future work. Note that our assessment is based on observations for 1950–99. As the ocean–U.S. connection is possibly time evolving (Hu and Feng 2001; Seager et al. 2009), it might exhibit different geographic features or seasonality during other time periods.

Finally, we stress that this work is not a mechanistic study but rather an observational diagnostic study of global SST–U.S. precipitation linkages. It does not answer why the SST modes force certain GHT response patterns in the first place. Neither does it exclude other physical explanations for these linkages. In some cases, more than one process may be responsible for the precipitation response. For instance, La Niña may produce a summertime dry condition in the northern Midwest by weakening both the upper-level westerly jet and low-level GPLLJ. A weakened westerly jet tends to suppress storm activity and precipitation while a weakened GPLLJ likely transports less moisture into the Midwest. To see their relative contribution to the dry anomalies, more quantitative moisture budget analyses are needed, which are beyond the scope of this work. On the other hand, dynamical experiments could be conducted to shed light on the mechanism of GHT response, and moreover, to investigate the accuracy of the GEFA as

done in the previous studies (Notaro et al. 2008; Notaro and Liu 2008; Zhong and Liu 2008).

REFERENCES

Alexander, M. A., I. Blade, M. Newman, J. R. Lanzante, N. C. Lau, and J. D. Scott, 2002: The atmospheric bridge: The influence of ENSO teleconnections on air–sea interaction over the global oceans. *J. Climate,* **15,** 2205–2231.

Anderson, D. L. T., E. S. Sarachik, P. J. Webster, and L. M. Rothstein, 1998: Preface. *J. Geophys. Res.,* **103,** 14 167.

Andrade, E. R., and W. D. Sellers, 1988: El Niño and its effect on precipitation in Arizona and western New Mexico. *Int. J. Climatol.,* **8,** 403–410.

Barlow, M., S. Nigam, and E. H. Berbery, 2001: ENSO, Pacific decadal variability, and U.S. summertime precipitation, drought, and stream flow. *J. Climate,* **14,** 2105–2128.

Bond, N. A., J. E. Overland, M. Spillane, and P. Stabeno, 2003: Recent shifts in the state of the North Pacific. *Geophys. Res. Lett.,* **30,** 2183, doi:10.1029/2003GL018597.

Booth, R. K., M. Notaro, S. T. Jackson, and J. E. Kutzbach, 2006: Widespread drought episodes in the western Great Lakes region during the past 2000 years: Geographic extent and potential mechanisms. *Earth Planet. Sci. Lett.,* **242,** 415–427.

Branstator, G., 2002: Circumglobal teleconnections, the jet stream waveguide, and the North Atlantic oscillation. *J. Climate,* **15,** 1893–1910.

Bunkers, M. J., J. R. Miller, and A. T. DeGaetano, 1996: An examination of El Niño–La Niña-related precipitation and temperature anomalies across the Northern Plains. *J. Climate,* **9,** 147–160.

Castro, C. L., T. B. McKee, and R. A. Pielke, 2001: The relationship of the North American monsoon to tropical and North Pacific Sea surface temperatures as revealed by observational analyses. *J. Climate,* **14,** 4449–4473.

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

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air–sea interactions. *Nature,* **385,** 516–518.

Chiang, J. C. H., and D. J. Vimont, 2004: Analogous Pacific and Atlantic meridional modes of tropical atmosphere–ocean variability. *J. Climate,* **17,** 4143–4158.

Cook, E. R., R. Seager, M. A. Cane, and D. W. Stahle, 2007: North American drought: Reconstructions, causes, and consequences. *Earth Sci. Rev.,* **81,** 93–134.

Czaja, A., and C. Frankignoul, 2002: Observed impact of Atlantic SST anomalies on the North Atlantic oscillation. *J. Climate,* **15,** 606–623.

Dai, A., I. Y. Fung, and A. D. Del Genio, 1997: Surface-observed global land precipitation variations during 1900–88. *J. Climate,* **10,** 2943–2962.

Davis, J. C., 1984: *Statistics and Data Analysis in Geology.* 2nd ed. John Wiley and Sons, 656 pp.

Deser, C., A. S. Phillips, and J. W. Hurrell, 2004: Pacific inter-decadal climate variability: Linkages between the tropics and the North Pacific during boreal winter since 1900. *J. Climate,* **17,** 3109–3124.

——, M. A. Alexander, S.-P. Xie, and A. S. Phillips, 2010: Sea surface temperature variability: Patterns and mechanisms. *Ann. Rev. Mar. Sci.,* **2,** 115–143.

Enfield, D. B., and D. A. Mayer, 1997: Tropical Atlantic sea surface temperature variability and its relation to El Niño–Southern Oscillation. *J. Geophys. Res.,* **102,** 929–945.

——, A. M. Mestas-Nunez, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental United States. *Geophys. Res. Lett.,* **28,** 2077–2080.

Frankignoul, C., and N. Sennechael, 2007: Observed influence of North Pacific SST anomalies on the atmospheric circulation. *J. Climate,* **20,** 592–606.

——, A. Czaja, and B. L'Heveder, 1998: Air–sea feedback in the North Atlantic and surface boundary conditions for ocean models. *J. Climate,* **11,** 2310–2324.

Giannini, A., R. Saravanan, and P. Chang, 2004: The preconditioning role of tropical Atlantic variability in the development of the ENSO teleconnection: Implications for the prediction of Nordeste rainfall. *Climate Dyn.,* **22,** 839–855.

Griffiths, M. L., and R. S. Bradley, 2007: Variations of twentieth-century temperature and precipitation extreme indicators in the northeast United States. *J. Climate,* **20,** 5401–5417.

Guan, B., and S. Nigam, 2008: Pacific sea surface temperatures in the twentieth century: An evolution-centric analysis of variability and trend. *J. Climate,* **21,** 2790–2809.

Gutzler, D. S., D. M. Kann, and C. Thornbrugh, 2002: Modulation of ENSO-based long-lead outlooks of southwestern U.S. winter precipitation by the Pacific decadal oscillation. *Wea. Forecasting,* **17,** 1163–1172.

Hoerling, M. P., and A. Kumar, 2003: The perfect ocean for drought. *Science,* **299,** 691–694.

——, J. W. Hurrell, and T. Y. Xu, 2001: Tropical origins for recent North Atlantic climate change. *Science,* **292,** 90–92.

Hoskins, B. J., and D. J. Karoly, 1981: The steady linear response of a spherical atmosphere to thermal and orographic forcing. *J. Atmos. Sci.,* **38,** 1179–1196.

Hu, Q., and S. Feng, 2001: Variations of teleconnection of ENSO and interannual variation in summer rainfall in the central United States. *J. Climate,* **14,** 2469–2480.

——, and ——, 2002: Interannual rainfall variations in the North American summer monsoon region: 1900–98. *J Climate,* **15,** 1189–1202.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kushnir, Y., W. A. Robinson, I. Blade, N. M. J. Hall, S. Peng, and R. Sutton, 2002: Atmospheric GCM response to extratropical SST anomalies: Synthesis and evaluation. *J. Climate,* **15,** 2233–2256.

Lau, K. M., J. Y. Lee, and I. S. Kang, 2004: The North Pacific as a regulator of summertime climate over Eurasia and North America. *J. Climate,* **17,** 819–833.

Liu, Z. Y., and L. X. Wu, 2004: Atmospheric response to North Pacific SST: The role of ocean–atmosphere coupling. *J. Climate,* **17,** 1859–1882.

——, and N. Wen, 2008: On the assessment of nonlocal climate feedback. Part II: EFA-SVD and optimal feedback modes. *J. Climate,* **21,** 5402–5416.

——, M. Notaro, J. Kutzbach, and N. Liu, 2006: Assessing global vegetation–climate feedbacks from observations. *J. Climate,* **19,** 787–814.

——, Y. Liu, L. Wu, and R. Jacob, 2007: Seasonal and long-term atmospheric responses to reemerging North Pacific Ocean variability: A combined dynamical and statistical assessment. *J. Climate,* **20,** 955–980.

——, N. Wen, and Y. Liu, 2008: On the assessment of nonlocal climate feedback. Part I: The generalized equilibrium feedback assessment. *J. Climate,* **21,** 134–148.

Mantua, N. J., and S. R. Hare, 2002: The Pacific decadal oscillation. *J. Oceanogr.,* **58,** 35–44.

Mestas-Nunez, A. M., 2000: Orthogonality properties of rotated empirical modes. *Int. J. Climatol.,* **20,** 1509–1516.

Mo, K., J. E. Schemm, and S. You, 2009: Influence of ENSO and the Atlantic multidecadal oscillation on drought over the United States. *J. Climate,* **22,** 6716–6740.

Montroy, D. L., 1997: Linear relation of central and eastern North American precipitation to tropical Pacific sea surface temperature anomalies. *J. Climate,* **10,** 541–558.

Mote, P. W., and Coauthors, 2003: Preparing for climatic change: The water, salmon, and forests of the Pacific Northwest. *Climatic Change,* **61,** 45–88.

Notaro, M., and Z. Liu, 2008: Statistical and dynamical assessment of vegetation feedbacks on climate over the boreal forest. *Climate Dyn.,* **31,** 691–712.

——, ——, and J. W. Williams, 2006a: Observed vegetation–climate feedbacks in the United States. *J. Climate,* **19,** 763–786.

——, W. C. Wang, and W. Gong, 2006b: Model and observational analysis of the northeast U.S. regional climate and its relationship to the PNA and NAO patterns during early winter. *Mon. Wea. Rev.,* **134,** 3479–3505.

——, Y. Wang, Z. Liu, R. Gallimore, and S. Levis, 2008: Combined statistical and dynamical assessment of simulated vegetation–rainfall during the mid-Holocene. *Global Change Biol.,* **14,** 347–368.

Peng, S. L., W. A. Robinson, S. L. Li, and M. P. Hoerling, 2005: Tropical Atlantic SST forcing of coupled North Atlantic seasonal responses. *J. Climate,* **18,** 480–496.

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

——, and ——, 1996: Quantifying Southern Oscillation–precipitation relationships. *J. Climate,* **9,** 1043–1059.

Roswintiarti, O., D. S. Niyogi, and S. Raman, 1998: Teleconnections between tropical Pacific sea surface temperature anomalies and North Carolina precipitation anomalies during El Niño events. *Geophys. Res. Lett.,* **25,** 4201–4204.

Schott, F. A., S. Xie, and J. P. McCreary Jr., 2009: Indian Ocean circulation and climate variability. *Rev. Geophys.,* **47,** RG1002, doi:10.1029/2007RG000245.

Schubert, S. D., M. J. Suarez, and P. J. Pegion, 2004: On the cause of the 1930s Dust Bowl. *Science,* **303,** 1855–1859.

——, and Coauthors, 2009: A U.S. CLIVAR project to assess and compare the responses of global climate models to drought-related SST forcing patterns: Overview and results. *J. Climate,* **22,** 5251–5272.

Seager, R., N. Harnik, W. A. Robinson, Y. Kushnir, M. Ting, H. P. Huang, and J. Velez, 2005a: Mechanisms of ENSO forcing of hemispherically symmetric precipitation variability. *Quart. J. Roy. Meteor. Soc.,* **131,** 1501–1527.

——, Y. Kushnir, C. Herweijer, N. Naik, and J. Velez, 2005b: Modeling of tropical forcing of persistent droughts and pluvials

over western North America: 1856–2000. *J. Climate,* **18,** 4065–4088.

——, and Coauthors, 2007: Model projections of an imminent transition to a more arid climate in southwestern North America. *Science,* **316,** 1181–1184.

——, A. Tzanova, and J. Nakamura, 2009: Drought in the southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change. *J. Climate,* **22,** 5021–5045.

Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes, 2002: The climate of the U.S. southwest. *Climate Res.,* **21,** 219–238.

Shin, S.-I., P. D. Sardeshmukh, and S. W. Robert, 2010: Optimal tropical sea surface temperature forcing of North American drought. *J. Climate,* **23,** 3907–3917.

Sutton, R. T., and D. L. R. Hodson, 2005: Atlantic Ocean forcing of North American and European summer climate. *Science,* **309,** 115–118.

Ting, M. F., and H. Wang, 1997: Summertime U.S. precipitation variability and its relation to Pacific sea surface temperature. *J. Climate,* **10,** 1853–1873.

Tourre, Y. M., B. Rajagopalan, and Y. Kushnir, 1999: Dominant patterns of climate variability in the Atlantic Ocean during the last 136 years. *J. Climate,* **12,** 2285–2299.

Venzke, S., M. Latif, and A. Villwock, 2000: The coupled GCM ECHO-2. Part II: Indian Ocean response to ENSO. *J. Climate,* **13,** 1371–1383.

Vimont, D. J., D. S. Battisti, and A. C. Hirst, 2001: Footprinting: A seasonal connection between the tropics and midlatitudes. *Geophys. Res. Lett.,* **28,** 3923–3926.

Wallace, J. M., C. Smith, and Q. Jiang, 1990: Spatial patterns of atmosphere–ocean interaction in the Northern Hemisphere. *J. Climate,* **3,** 990–998.

——, E. M. Rasmusson, T. P. Mitchell, V. E. Kousky, E. S. Sarachik, and H. von Storch, 1998: The structure and evolution of ENSO-related climate variability in the tropical Pacific: Lessons from TOGA. *J. Geophys. Res.,* **103,** 14 241–14 259.

Wang, C., D. B. Enfield, S. Lee, and C. W. Landsea, 2006: Influences of the Atlantic warm pool on Western Hemisphere summer rainfall and Atlantic hurricanes. *J. Climate,* **19,** 3011–3028.

——, S. Lee, and D. B. Enfield, 2007: Impact of the Atlantic warm pool on the summer climate of the Western Hemisphere. *J. Climate,* **20,** 5021–5040.

Wang, H., and M. F. Ting, 2000: Covariabilities of winter U.S. precipitation and Pacific sea surface temperatures. *J. Climate,* **13,** 3711–3719.

Weaver, S. J., S. Schubert, and H. Wang, 2009: Warm season variations in the low-level circulation and precipitation over the central United States in observations, AMIP simulations, and idealized SST experiments. *J. Climate,* **22,** 5401–5420.

Wen, N., Z. Liu, Q. Liu, and C. Frankignoul, 2010: Observed atmospheric responses to global SST variability modes: A unified assessment using GEFA. *J. Climate,* **23,** 1739–1759.

White, W. B., A. Gershunov, and J. Annis, 2008: Climatic influences on Midwest drought during the twentieth century. *J. Climate,* **21,** 517–531.

Willmott, C. J., and K. Matsuura, 1995: Smart interpolation of annually averaged air temperature in the United States. *J. Appl. Meteor.,* **34,** 2577–2586.

Wu, R., and L. Kinter III, 2008: An analysis of the relationship of U.S. droughts with SST and soil moisture: Distinguishing the time scales of droughts. *J. Climate,* **22,** 4520–4538.

Xie, S.-P., 1999: A dynamic ocean–atmosphere model of the tropical Atlantic decadal variability. *J. Climate,* **12,** 64–70.

——, and S. G. H. Philander, 1994: A coupled ocean–atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus,* **46A,** 340–350.

——, and J. A. Carton, 2004: Tropical Atlantic variability: Patterns, mechanisms, and impacts. *Earth Climate: The Ocean–Atmosphere Interaction, Geophys. Monogr.,* Vol. 147, Amer. Geophys. Union, 121–142.

Yu, J. Y., and K. M. Lau, 2004: Contrasting Indian Ocean SST variability with and without ENSO influence: A coupled atmosphere–ocean GCM study. *Meteor. Atmos. Phys.,* **90,** 179–191.

Zhong, Y., and Z. Liu, 2008: A joint statistical and dynamical assessment of atmospheric response to North Pacific oceanic variability in CCSM3. *J. Climate,* **21,** 6044–6051.

——, and ——, 2009: On the mechanism of Pacific multidecadal climate variability in CCSM3: The role of subpolar North Pacific Ocean. *J. Phys. Oceanogr.,* **39,** 2052–2076.

——, ——, and R. Jacob, 2008: Origin of Pacific multidecadal variability in Community Climate System Model, version 3 (CCSM3): A combined statistical and dynamical assessment. *J. Climate,* **21,** 114–133.