How Well Can a Climate Model Simulate the Response of Summer Rainfall in the Southeast United States to Tropical Sea Surface Temperature Anomalies?

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Abstract

We have examined the National Center for Atmospheric Research (NCAR) Community Atmospheric Model Version 3.5 (CAM3.5) to determine how realistic the model can simulate summer rainfall climatology and anomalies in the Southeast United States (SE US) and their relationship with the sea surface temperature anomalies (SSTA) over the adjacent tropical oceans. Our results suggest that the model reasonably well simulates the climatology and the range of the climate variability of the rainfall over US, but cannot capture the years of the interannual drier or wet anomalies and decadal scale change of the precipitation in US. The circulation pattern associated with the interannual dry anomalies over the SE US is similar to that observed although the low-level anticyclonic circulation center bias southward. The teleconnection between the rainfall over the SE US and the SSTA over the Pacific is well captured, but that with the Atlantic SSTA is not by the model. Further analysis suggests that inadequate linkage between SSTA in the Atlantic, the Bermuda High, which influences moisture transport from Gulf of Mexico, and rainfall in the SE US is at least in part responsible for lack of predictability of summer rainfall anomalies in SE US shown in CAM3.5.

1. Introduction

In recent decades, the Southeast United States (SE US) has experienced multiple severe droughts. The most recent one was classified as an exceptional drought, starting from winter 2005 and lasting until November 2008. During this drought, many locations over the SE US had annual rainfall deficits of 20 inches or more, leading to a record low precipitation for the past hundred years (Fuchs, 2008; Manuel 2008). Along with the dryness, the region also experienced several months of above normal temperatures and extended heat waves in summer. This drought caused $1.3 billion of agriculture loss in the SE US during 2007 based on the estimate by the National Drought Mitigation Center. Observed precipitation data suggest an increase in the magnitude of the summer rainfall anomalies, including droughts, over the SE US since mid 1980s (Wang et al., 2009). Given rapid increase of the population in the drought prone regions in the US, the need for understanding of the mechanism of the drought and an explanation of its predictability is becoming increasingly urgent for water resource management.

To address this need, the US Climate Variability and Predictability (CLIVAR) Drought Working Group has coordinated with several major climate modeling groups in the US. A suite of idealized experiments are carried out to investigate influences of sea surface temperature anomalies in the tropical oceans on drought in the US as represented in these models, and to explore the feasibility of these models for drought prediction (Schubert et al. 2008). Although these climate models exhibit a consistent and robust response of US rainfall anomalies to sea surface temperature anomalies in the Pacific, they have shown considerable discrepancies and ambiguities in the response of rainfall over the US to sea surface temperature anomalies (SSTA) in the Atlantic Ocean. The signal to noise ratio is also lower in the SE US than in other parts of the US. Wang et al. (2009) have shown observationally that summer rainfall anomalies in the SE US are significantly correlated to sea surface temperature anomalies in the tropical Atlantic Ocean. Thus, there is a considerable potential predictability for the summer rainfall in this region based on SST anomalies, in contrast to the lack of predictability shown by climate models (Seager et al., 2008).

This work evaluates the National Center for Atmospheric Research (NCAR) Community Atmosphere Model Version 3.5 (CAM3.5) in terms of the realism of its summer rainfall anomaly simulations in the SE US and their relationship with SSTA in the tropical oceans. We evaluate this model primarily because it provides long enough simulations forced by the observed SST at relatively high spatial resolution (T85). This interval we use in the work (1948-2006) would allow us to examine more drought events on regional scale compared to less than 30-year simulations (1979-2006) provided by most of other climate models that participated in the US Drought Working Group simulations. Given the ambiguous response of US rainfall anomalies to the SST anomalies in the Atlantic Ocean in most of the climate models that participated in the US Drought Working Group (Schubert et al., 2009), our result may serve as an informative first step to address this problem as it exists in other climate models.

2. Data and Methods

The model output we analyzed is the 59-year simulations of NCAR CAM3.5 forced by the prescribed SST estimated from observations for the period of 1948-2006, from http://dsrs.atmos.umd.edu/DATA/CAM3.5_DWG/AMIP/. The time periods of the datasets span from 1871 to 2006 and the model's resolution is T85 (about 150 km). More detailed description about the improvements relative to the previous version CAM3.0 can be found in Neale et al. (2008) and Oleson et al. (2008).

We also used observations of precipitation, and sea surface temperature from 1948 to 2006 to evaluate the simulations of the model. In particular, the NOAA Climate Prediction Center (CPC) U.S. Unified Precipitation for 1948–98 and the real-time U.S. Daily Precipitation Analysis for 1999–2006, and the NOAA Extended Reconstructed SST (ERSST v3, Smith et al. 2008), respectively, are used. An index for the SE US summer rainfall anomalies, referred to as the PA_{SE} thereinafter, is constructed by averaging precipitation anomalies during June to August in an area from 76^{o}W to 91^{o}W and from 25^{o}N to 36.5^{o}N. The area covers seven southeastern states, namely Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, and Tennessee. The National Center for Environmental Prediction (NCEP) reanalysis product is used as a surrogate for observations of the large-scale circulation changes. This reanalysis product provides 6-hour instantaneous values of wind, geopotential height, temperature and specific humidity, along with many other meteorological variables from the sea-level to above troposphere at different pressure levels at a 2.5-degree spatial resolution for the same period 1948-2006 (Kalnay et al., 1996).

Wang et al. (2009, in this issue) have examined the observed relationships between the Southeast summer precipitation anomalies, the atmospheric circulation changes, and tropical SSTs using the singular value decomposition (SVD; Bretherton et al., 1992). This study uses a similar statistical analysis to determine whether the patterns of observed relationship characterized by Wang et al. (2009) are adequately captured by the CAM3.5 simulations.

3. Results

3.1 How well can CAM3.5 simulate the climatology and variance of the summer rainfall over SE US?

Figure 1 shows the modeled precipitation climatology and their variances over the US relative to those from observations. In the summer season (June, July and August), observed precipitation gradually increases from west to east, and regions of maximum mean precipitation (>5 mm day^{-1}) are along the Gulf coast, Florida State and east coast of the US (Figure 1a). CAM3.5 has reasonably simulated the gradually increase of precipitation from less than 1 mm day^{-1} in the southwest to over 5 mm day^{-1} in the eastern US. However, the summer mean precipitation in the model is as much as 60% stronger in the southeastern US and central Great Plains than in observation (Figure 1c). Figures 1b and 1d suggest that the modeled precipitation overestimates the variance over the west part of the continent (100^{o}W) by about 50%, and underestimates it along the Gulf coast and Florida State.

Figure 2 shows the time series of the PA_{SE} normalized by its standard deviation for the period of 1948–2006 from the observation, and CAM3.5, respectively. The observation displays higher interannual variability with more wet and dry extremes in the second half of the period (i.e. 1978-2006, also see Wang et al., 2009). The CAM3.5 model is able to capture the observed increase of dry events in the SE US, although the magnitude is not as strong as observed (Figure 2a). However, the model is unable to simulate the observed increase of frequency and magnitude of wet anomalies, because they are overestimated for the 1st period and underestimated for the 2nd period compared to observation. The dry/wet years in the model also do not match with those observed (Figure 2b). The model does not capture the decadal variability of precipitation change as observed for the period of our analysis (Figure 2b).

In summary, the model qualitatively captures mean summer rainfall over the southwest US but tends to overestimate its amount and variance over the SE US. It shows an increase of negative rainfall anomalies on decadal scale as observed, but is unable to capture the years of the observed dry and wet anomalies. Overall, the interannual and decadal variability of SE US rainfall anomalies in the model are not very reliably simulated.

3.2 How well does the model capture the circulation changes associated with the SE US rainfall anomalies?

The continental-scale warm season rainfall in the United States is controlled by the large-scale atmospheric circulation (Liu et al., 1998); therefore the changes of modeled general circulation associated with the SE US rainfall anomalies are compared with those in observations. Specifically, we analyzed the upper- and low-level circulation anomalies associated with Southeast summer droughts using linear regressions of the geopotential and wind fields vs. the modeled Southeast summer precipitation index. Observations indicate positive height anomalies over the south-central and southeastern US (Fig. 3a) accompanying by a stronger upper-level jet stream at 200h-Pa; Underneath this anomalous center of upper level geopotential height, an anomalous anticyclonic flow enhances low-level jet over the Great Plains and moisture transport from the Gulf of Mexico to the Midwest, as well as transports drier continental air from the north-central US to the SE US (Fig. 3b).

Comparing to observations, CAM3.5 model captures the pattern of the positive anomalous of geopotential height at 200-hPa associated with the one standard deviation of dry PA_{SE} although the height anomalies are much stronger in the high latitudes of North America than those observed (Fig. 3c). At 850-hPa, the anticyclonic flow over the south-central and southeastern US is reasonably captured by the model, but the anticyclonic circulation is slightly biased to the south (2~3 degree south) compared to observations (Fig. 3d). The anomalous cyclonic center over the North Atlantic is not as well formed as that observed and too far northward.

3.3 How well does the model capture the teleconnection between SE US rainfall and SSTA in the adjacent tropical oceans?

Wang et al. (2009) have shown clear observational connections of the Southeast precipitation to Pacific and Atlantic SSTs. Those connections are reproduced in Fig. 4 for the convenience of comparison with the model. In Fig. 4a, the homogeneous correlation pattern of the SST anomalies for the first SVD mode between the Pacific SST anomalies and the summer US rainfall anomalies, referred to as the corresponding SST anomalies pattern for this SVD mode, resembles the El Niño pattern. Similarly, the homogeneous correlation pattern between this first SVD mode and the US summer precipitation anomalies is referred to as the corresponding precipitation anomalous pattern for this SVD mode (Fig. 4b). The latter suggests a strong increase of rainfall in the mid-west US and weakly decrease of rainfall in the SE US, associated with El Niño-like SST anomalies in the Pacific. Similarly, Figures 4c and 4d show the homogeneous correlation patterns associated with the first SVD mode between the Atlantic SST anomalies and the summer US rainfall anomalies. The figures suggest a strong increase of rainfall in the SE US and Texas associated with warming over the North Atlantic, the tropical Atlantic and the eastern South Atlantic, as well as the western Pacific and tropical Indian Oceans. Figure 4f shows the homogeneous correlation patterns for the second SVD mode between the Atlantic SST anomalies (Fig. 4e) and the summer US rainfall anomalies. This figure suggests a strong decrease of rainfall in the SE US associated with warmer SST anomalies in the tropical Atlantic Ocean.

Figure 5 shows a similar SVD analysis applied to the covariance matrices of modeled summer season U.S. rainfall anomalies and the observed SST anomalies over the Pacific and Atlantic basin, respectively. The modeled patterns for both SST and rainfall anomalies corresponding to the first SVD mode between the Pacific SST anomalies (Fig. 5a) and summer US rainfall anomalies (Fig. 5b) agree in general with those observed (Figures 4a and 4b) in spite of the spurious increase (decrease) of rainfall in Oregon and Nevada (northeastern states) in the model. The SST anomalies pattern corresponding to the first SVD mode between the Atlantic SST anomalies and US summer rainfall anomalies (Fig. 5c) also agrees well with that observed (Fig. 4c). However, the modeled corresponding rainfall pattern for this SVD mode shows a strong increase of rainfall in the mid-west US (Fig. 5d), instead of over Texas as observed (Fig. 4d). The corresponding SST pattern for the second SVD between the Atlantic SST anomalies and the US summer rainfall anomalies (Fig. 5e) shows a dipole pattern with the warming centered in the southeastern tropical Atlantic, instead of over the entire tropical Atlantic as observed (Fig. 4e). Instead of observed drier rainfall anomalies in the SE US (Fig. 4f), the modeled corresponding rainfall anomalies pattern for this second SVD mode indicates wetter rainfall anomalies in the SE US and drier rainfall anomalies over the northeastern half of the US continent (Fig. 5f). Figure 5 suggests that the NCAR CAM3.5 model generally captures the covariability between the US summer rainfall and El Niño-like Pacific SST anomalies. However, it does not adequately capture the covariability between the US summer precipitation anomalies and the Atlantic SST anomalies.

3.4 What may cause the modeled weak link between Atlanta Ocean and the SE US rainfall anomalies?

Wang et al. (2009) have suggested that the interannual and decadal variations of the Atlantic SST may contribute to the observed summer rainfall anomalies on both temporal scales. Yet, the model appears unable to capture such connections. What might contribute to this model deficiency? Observations have demonstrated a strong connection between the moisture transport to the SE US and the location of the Bermuda High (also known as Azores High). The western edge of this semi-permanent high pressure in the North Atlantic Ocean migrates east and west with varying central pressure (Davis et al., 1997). During the Northern Hemispheric summer and fall, the center is located in the western North Atlantic, near Bermuda. Along its western edge, warm and humid air from the tropical Atlantic and Gulf of Mexico is transported by anticyclonic southerly flow to the eastern United States. When the Bermuda High is displaced westward, it shifts the warm and humid southerly air flow westward, enhancing the moisture transport to the Great Plains and weakening the moisture transport to the SE US. Thus, an adequate simulation of the Bermuda High and its climate variability is likely important for determining the climate variability of summer rainfall anomalies over the Great Plains and the SE US. What processes control the climate variability of the Bermuda High is still a subject of active study. In this work, we evaluate whether the Bermuda High and its relationship with the Atlantic SST anomalies are adequately modeled in the NCAR CAM3.5. We apply SVD analysis to the Atlantic SST anomalies versus the sea level pressure (SLP) in the north Atlantic and the SLP versus the precipitation over the US in summer, respectively.

Observations show that during summer, the center of the Bermuda High locates in the area of 30^o-40^oN and 30^o-40^oW (Fig. 6a) although the system could range 20^oN-45^oN and 80^oW-10^oW. The variance of the SLP near the high center is about 1-3 hPa (Fig. 6b). The NCAR CAM3.5 model generally captures the climatological mean of the summer SLP over the Atlantic Ocean (Fig. 6c). However, it overestimates the SLP by about 2-4 hPa and the center of the Bermuda High is wider and biased eastward (Fig. 6c). The standard deviation of the observed summer SLP has qualitatively captured by the NCAR CAM3.5 model although the variance of the modeled summer SLP may be slightly overestimated over the mid-west, northeastern US and north of SE US and North Atlantic Ocean (Fig. 6d). Such a more southward extension of the strong SLP variability (Fig. 6d) is consistent with the southward bias of the low-level anticyclonic circulation (Fig. 3d), which leads to overestimate of rainfall variability in SE US (Fig. 3d).

The SVD analysis is applied to the observed summer U.S. precipitation and the SLP over the Atlantic Ocean (20^o-45^oN 80^o-10^oW). Two precipitation patterns are objectively identified that have significant loadings in the Southeast and are coupled with the Bermuda High (Fig. 7). The first SVD mode explains 35% of the squared covariance between the Atlantic SLP and U.S. precipitation, and is characterized by the westward expansion of Bermuda High, with the large negative correlations in the eastern coast of the US (Fig. 7a). The corresponding precipitation (Fig. 7b), which explains 10% of the total summer U.S. precipitation variance, displays negative correlations in the Southeast, southern and northeastern US, and positive correlations in the western and northern US. The correlation between the Bermuda High and US precipitation as represented by the first SVD mode (Fig. 7b) is 60%.

The second SVD mode explains 31% of the squared covariance, featuring the eastward of the Bermuda High (Fig. 7c). The precipitation pattern shows coherent positive correlations in the Southeast, southern and northeast US, and negative correlations in the western and northern US (Fig. 7d). This mode accounts for 10% of the precipitation variance over the US. Thus, observation suggests that a weakening of the Bermuda High over its western part (over the Northwest Atlantic) tends to reduce rainfall in the SE US, whereas a weakening of the Bermuda High over its eastern part (over the Northeast Atlantic) tends to increase rainfall in the SE US.

The model fails to capture the co-variability of the SLP and summer precipitation in the SE US (Figures 7e-7h). The first SVD mode of the Bermuda High features the enhancement of the SLP over the tropical and subtropical north Atlantic, centering at 30^o-35^oN, 50^oW (Fig. 7e); the 2^{nd} SVD mode displays the center of the SLP northward around 40^o-45^oN, 50^oW (Fig. 7g), in disagreement from that observed. The corresponding precipitation patterns (Figures 7f and 7h) thus do not resemble those observed (Figures 7b and 7d). Thus, the model has not provided the linkage between the SLP variation and summer precipitation change in the US as observations suggested.

Could the tropical Atlantic SST influence the changes of the Bermuda High? To answer the question, the SVD analysis between the two fields has been employed as shown in Fig. 8. The first SVD mode explains 66% of the squared covariance between the Atlantic SST and the Bermuda High featuring a warming in tropical and north Atlantic (Fig. 8a). The corresponding SLP mode (Fig. 8b) explains 18% of the total summer SLP variance. The correlation between the pair of the first SVD mode time series of the Atlantic SST and Bermuda High (Fig. 8b) is 61%, i.e., above the 99% confidence level based on a Monte Carlo test.

The second SVD mode explains 13% of the squared covariance, featuring the warming in tropical Atlantic (Fig. 8c). The corresponding SLP mode (Fig. 8d) explains 14% of the total summer SLP variance, similar to the first mode. The mode exhibits a weakened Bermuda High westward centering in the area of 50^oW-70^oW and 35^o-45^oN.

Observations (Figures 7 and 8) suggest that the warming in tropical and north Atlantic is linked to a weaker eastern Bermuda High and enhancement of precipitation over the SE US (Figures 7b and 7c), whereas warming in the tropical and south Atlantic is connected to a weakened southwest part of the Bermuda High and precipitation reduction over the SE US (Figures 7a and 7b).

In NCAR CAM3.5 model, the first mode reasonably captures the warming in the tropical and north Atlantic (Fig. 8e). The corresponding SLP anomaly resembles that of observation (Fig. 8f). However, the second mode of SST field shows that warming in the south tropical Atlantic (Fig. 8g) is linked to an extensive enhancement of SLP in the southwest part of the Bermuda High over the subtropical western Atlantic, differing from that observed (Fig. 8d).

4. Discussion

4.1 The importance of the Atlantic Ocean in determining the climate variability of the summer rainfall over the SE US

Observations suggest that variability of the US summer precipitation is coupled with the Atlantic and Pacific SST variations (Schubert et al., 2009; Wang et al., 2009). Over the SE US, the Atlantic SST anomalies appear to have a stronger influence on the climate variability of the summer rainfall, especially on multi-decadal scales. In particular, the intensification of the Southeast summer rainfall variability is primarily associated with higher Atlantic SST variability in the recent three decades (Wang et al., 2009). The atmospheric models forced by observed SST, however, have been shown considerable discrepancies from the observation in terms of the response of rainfall anomalies over the US to SST anomalies. The NCAR CAM3.5 model reasonably well captures the co-variability of the Pacific SST and the summer precipitation over the SE US. However, its inability to represent the observed connections between the summer rainfall anomalies over the SE US to the Atlantic SST likely contributes to its lack of predictability for SE US drought.

4.2 What might cause the lack of predictability for the SE US summer rainfall anomalies in a climate model?

The Bermuda High dominates the summer circulation over the Atlantic Ocean and eastern US, especially the location and strength of the low-level moisture transport to the eastern and central US (Davis et al., 1997). Although many factors could possibly influence the location and intensity of this high system, our study suggests that the Atlantic SST anomalies contribute to the variability of the Bermuda High. The SVD analysis between the Atlantic SST and SLP fields suggest that the model reasonably capture the covariability with the north Atlantic SST, but not with SST over the tropical Atlantic, especially over the south tropical Atlantic as shown by the 2nd SVD mode. The 2nd SVD mode contributes to the SLP variance a similar percentage as that of the 1st SVD mode. The first two SVD modes between the SLP and precipitation fields do not show any resemblances between the model and the observations. Thus, an inadequate representation of Bermuda High and its link to Atlantic SST anomalies and US summer rainfall anomalies may contribute to the lack of predictability for the SE US summer rainfall anomalies in CAM3.5.

5. Conclusion

Observational studies have shown that the higher Atlantic SST variability contributes to the enhancement of the summer rainfall variations including drought events over the SE US in recent decades. This result indicates a potential for prediction for the summer rainfall in the region. However, such a connection is not captured by most of the major US climate models. Using the NCAR CAM3.5 as an example, we analyzed the possible reasons of such discrepancies between the models forced by realistic SSTs and observation. Our results suggest that the model reasonably well simulates the climatology and variation of the precipitation changes over the western US but overestimates them over the SE US. The increase of dry extremes in the 2nd half period is captured by the model, but the model is unable to capture the years of the observed dry and wet anomalies.

The model reasonably simulated the circulation pattern associated with the dry events over the SE US but the low-level anticyclonic circulation center is about 2-3 degree too southward. Our results also indicate that the NCAR CAM3.5 model generally captures the covariability between the US summer rainfall and El Niño-like Pacific SST anomalies, but does not adequately capture the covariability between the US summer precipitation anomalies and the SST anomalies over the Atlantic Ocean. A possible reason is the lack of linkage between the SSTA in the Atlantic, especially the tropical SSTA with the Bermuda High, which influences the pattern of moisture transports. Our results suggest that a clearer understanding of the underlying processes that control this linkage and improvement in the treatment of these processes in climate models is a key step toward improve the predictability of the SE US summer rainfall anomalies.

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Figure Captions:

Figure 1. The seasonal mean (left, Unit: mm day^{-1}) and standard deviation (right, Unit: mm day^{-1}) of the U.S. precipitation based on rainfall data from 1948 to 2006. The observed results are shown in the upper panels and the modeled results are shown in the lower panels, respectively.

Figure 2. Normalized time series of summer (June-August) mean precipitation anomalies averaged over the Southeastern United States (25°–36.5°N, 76°–91°W) from (a) the observations and (b) that simulated by NCAR CAM3.5. Black bars represent wet and dry summers with normalized precipitation anomalies exceeding one standard deviation, which is indicated by dashed lines. A vertical line divides the first 30-year and second 29-year periods.

Figure 3. Anomalous summer (June-August) 200-hPa height (shading) and zonal wind (contour, a and c), and 850-hPa wind (vector, b and d) and the U.S. precipitation anomalies (shading, b and d) associated with one standard deviation of rainfall deficit in the Southeast summer rainfall index. Contour intervals are 0.5 m s^{-1} and 1 m s^{-1} in a) and c), respectively. Linear regressions of 200-hPa height (zonal wind) anomalies greater than 5 and 10 gpm (0.5 and 1.5 m s^{-1}) are significant in observation and model respectively as estimated by the Monte Carlo tests at 95% significance level in a) and c). Regression of 850-hPa zonal (meridional) wind anomalies greater than 0.2 and 0.4 m s^{-1} (0.1 and 0.3 m s^{-1}) are significant in observation and model respectively as estimated by the Monte Carlo tests at 95% significance level in b) and d).

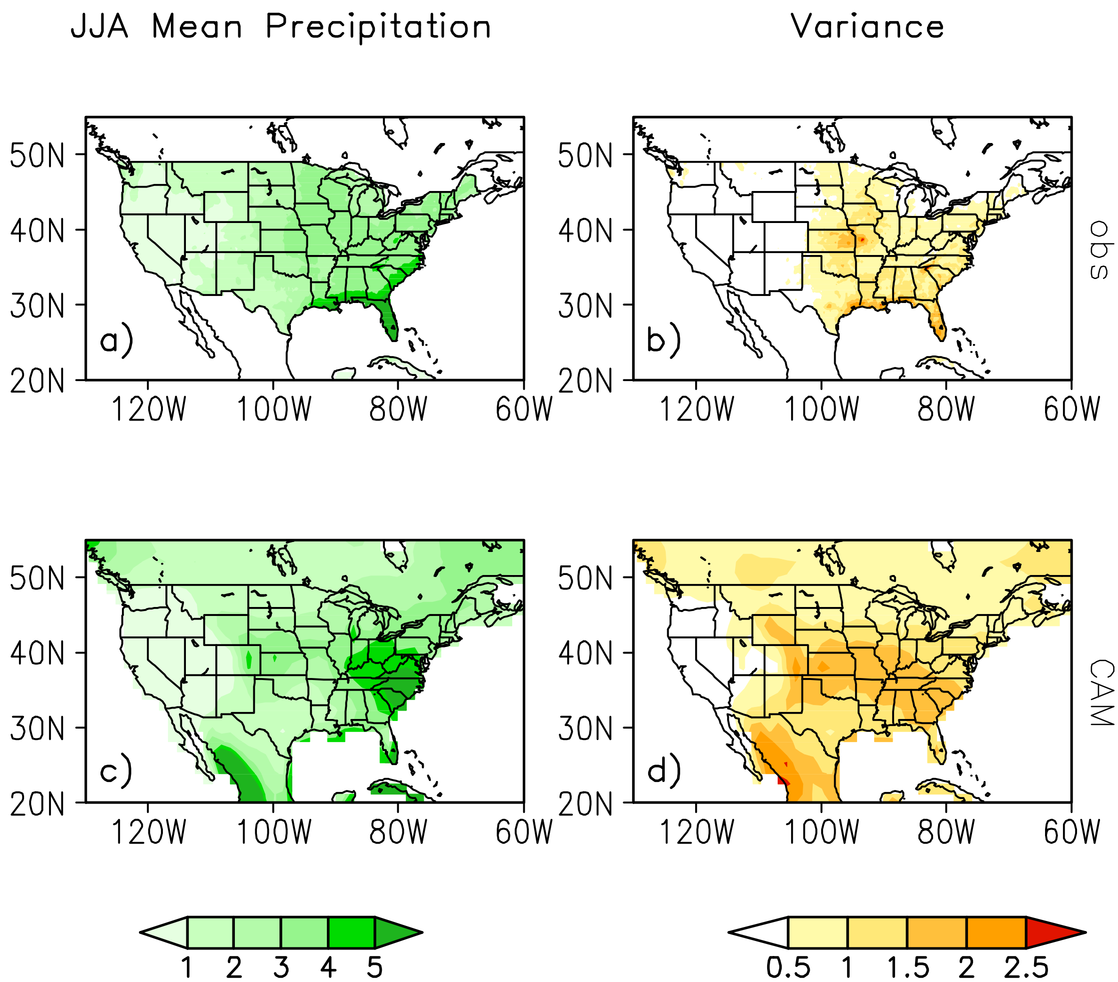
Figure 4: Homogeneous correlation maps of the first SVD mode (a,b) between Pacific SST and U.S. precipitation, the first (c,d) and second SVD (e,f) modes between Atlantic SST and U.S. precipitation. Correlation coefficients exceeding the 95% significance level estimated by the Monte Carlo tests are shaded by gray. Positive values of 0.3, 0.5 and 0.7 are also contoured. The dashed-line boxes indicate the domain of SST used in the SVD analyses.

Figure 5. As in Fig. 4 but for NCAR CAM3.5 except in the right panels, Correlation coefficients exceeds the 85% significance level estimated by the Monte Carlo tests are shaded by gray.

Figure 6. The summer seasonal mean (a and c, Unit: hPa) and standard deviation (b and d, Unit: hPa) of sea level pressure for the period of 1948-2006 from the observation (a and b) and from NCAR CAM3.5 (c and d), respectively.

Figure 7. Homogeneous correlation maps of the first (a, b, e, f) and second (c, d, g, h) SVD modes between SLP over the tropical Atlantic and U.S. precipitation from observation (a, b, c, d) and NCAR CAM3.5 model (e, f, g, h). Correlation coefficients exceeding the 95% significance level estimated by the Monte Carlo tests are shaded for left panels; Correlation coefficients greater than 0.2 are significant as estimated by the Monte Carlo tests at 95% (85%) significance level in b) and d) (g) and h)) respectively.

Figure 8. Homogeneous correlation maps of the first (a, b, e, f) and second (c, d, g, h) SVD modes between the tropical Atlantic SST and SLP from the observation (a, b, c, d) and NCAR CAM3.5 (e, f, g, h). Correlation coefficients greater than 0.3 for SST anomalies and 0.5 for SLP anomalies are shaded above 95% significant level as estimated by the Monte Carlo test.



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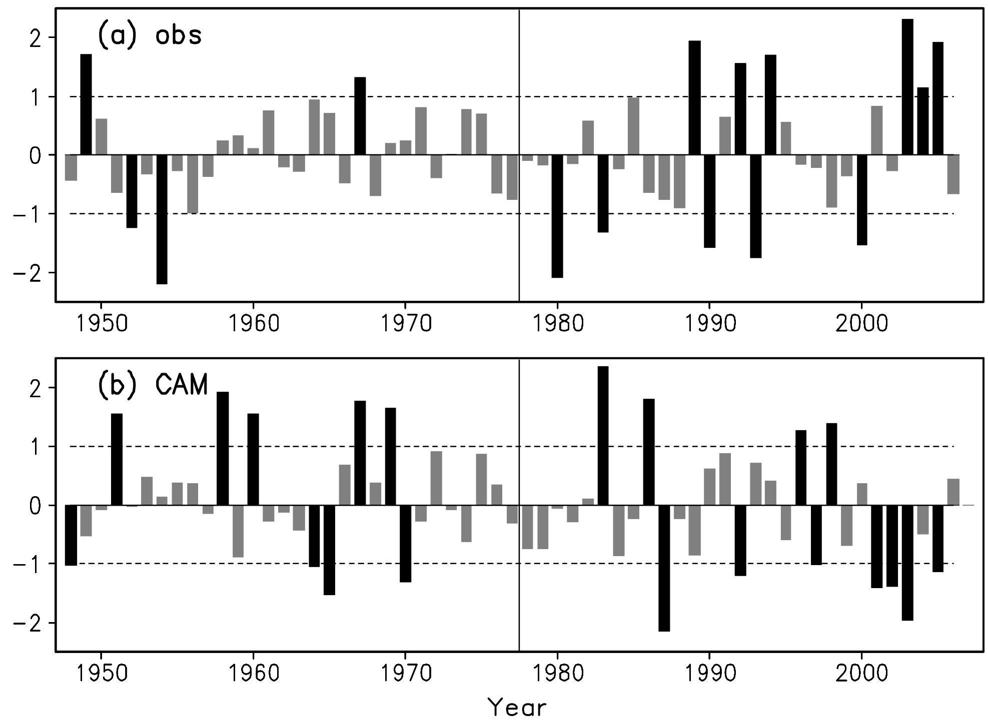

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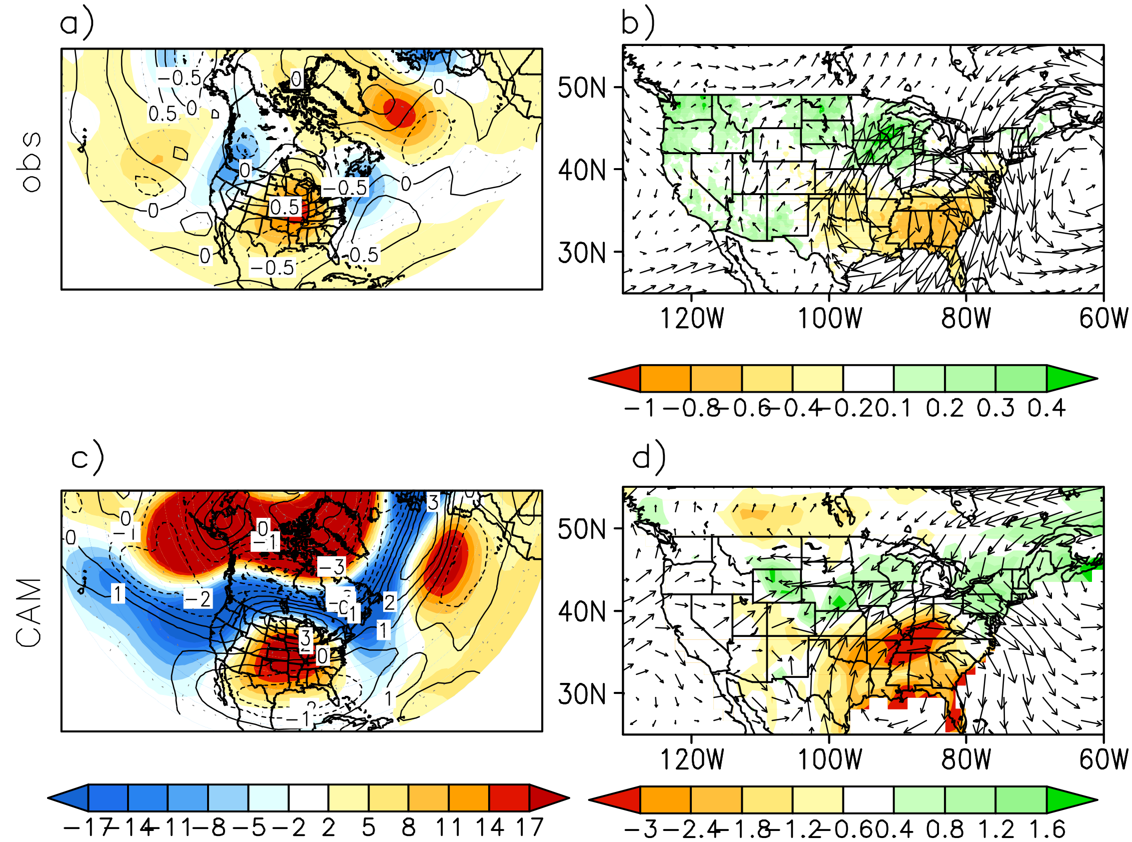

Figure 3. Anomalous summer (June-August) 200-hPa height (shading) and zonal wind (contour, a and c), and 850-hPa wind (vector, b and d) and the U.S. precipitation anomalies (shading, b and d) associated with one standard deviation of rainfall deficit in the Southeast summer rainfall index. Contour intervals are 0.5 m s^{-1} and 1 m s^{-1} in a) and c), respectively. Linear regressions of 200-hPa height (zonal wind) anomalies greater than 5 and 10 gpm (0.5 and 1.5 m s^{-1}) are significant in observation and model respectively as estimated by the Monte Carlo tests at 95% significance level in a) and c). Regression of 850-hPa zonal (meridional) wind anomalies greater than 0.2 and 0.4 m s^{-1} (0.1 and 0.3 m s^{-1}) are significant in observation and model respectively as estimated by the Monte Carlo tests at 95% significance level in b) and d).

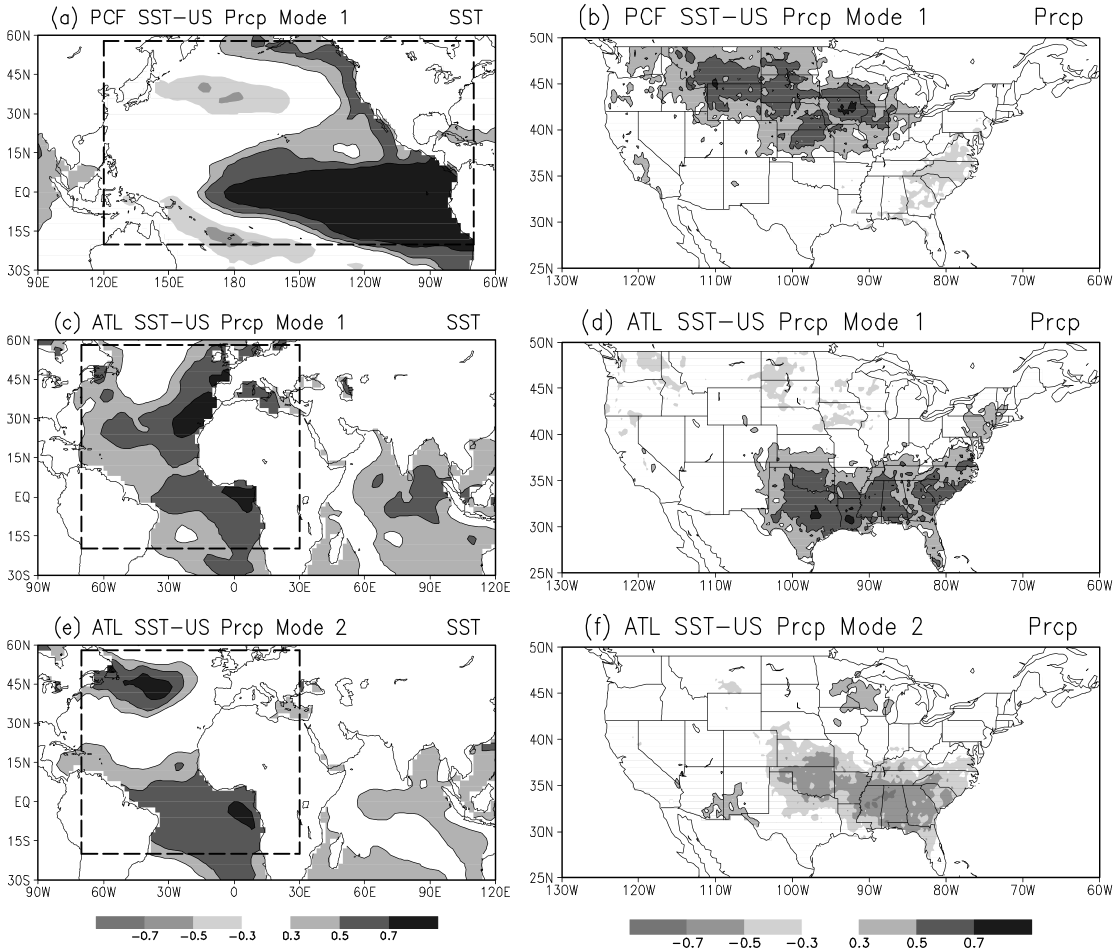

Figure 4: Homogeneous correlation maps of the first SVD mode (a,b) between Pacific SST and U.S. precipitation, the first (c,d) and second SVD (e,f) modes between Atlantic SST and U.S. precipitation. Correlation coefficients exceeding the 95% significance level estimated by the Monte Carlo tests are shaded by gray. Positive values of 0.3, 0.5 and 0.7 are also contoured. The dashed-line boxes indicate the domain of SST used in the SVD analyses.

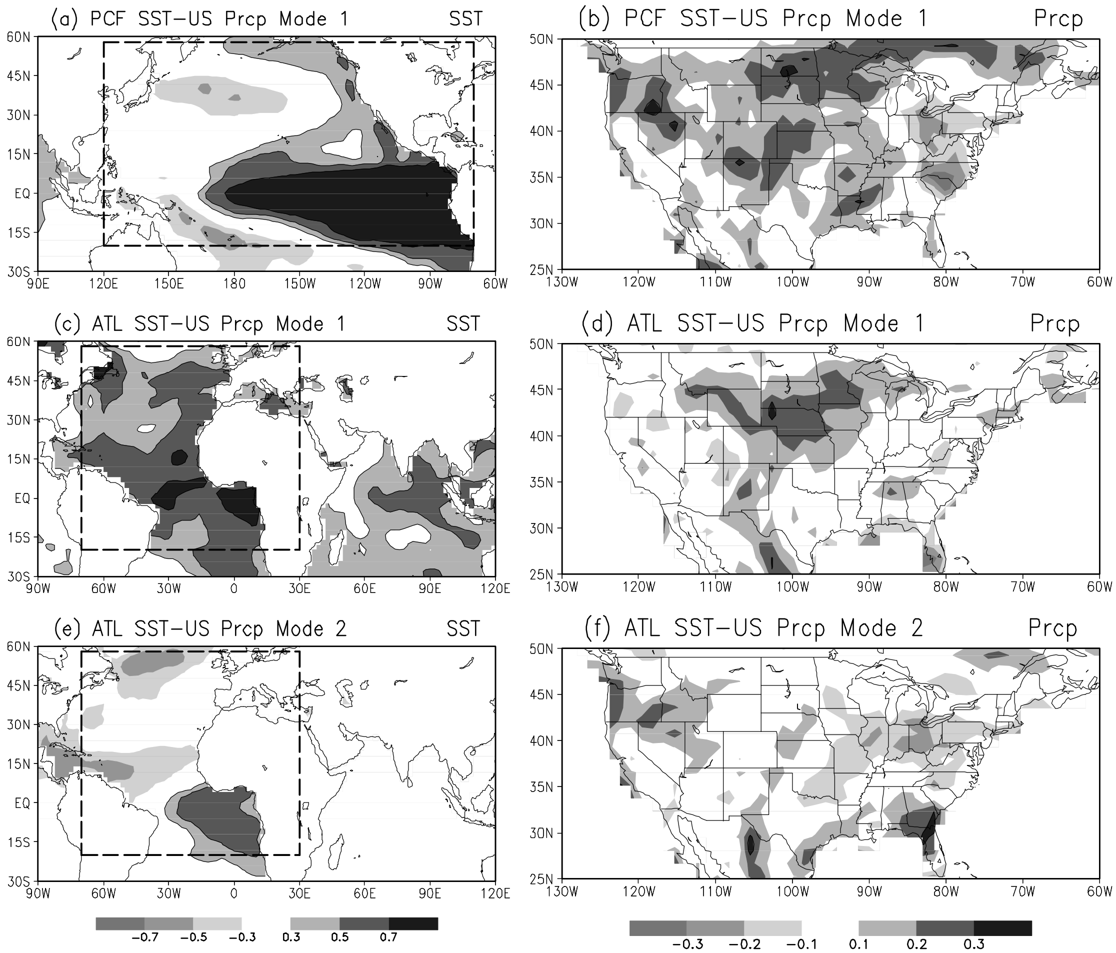

Figure 5. As in Fig. 4 but for NCAR CAM3.5 except in the right panels, Correlation coefficients exceeds the 85% significance level estimated by the Monte Carlo tests are shaded by gray.

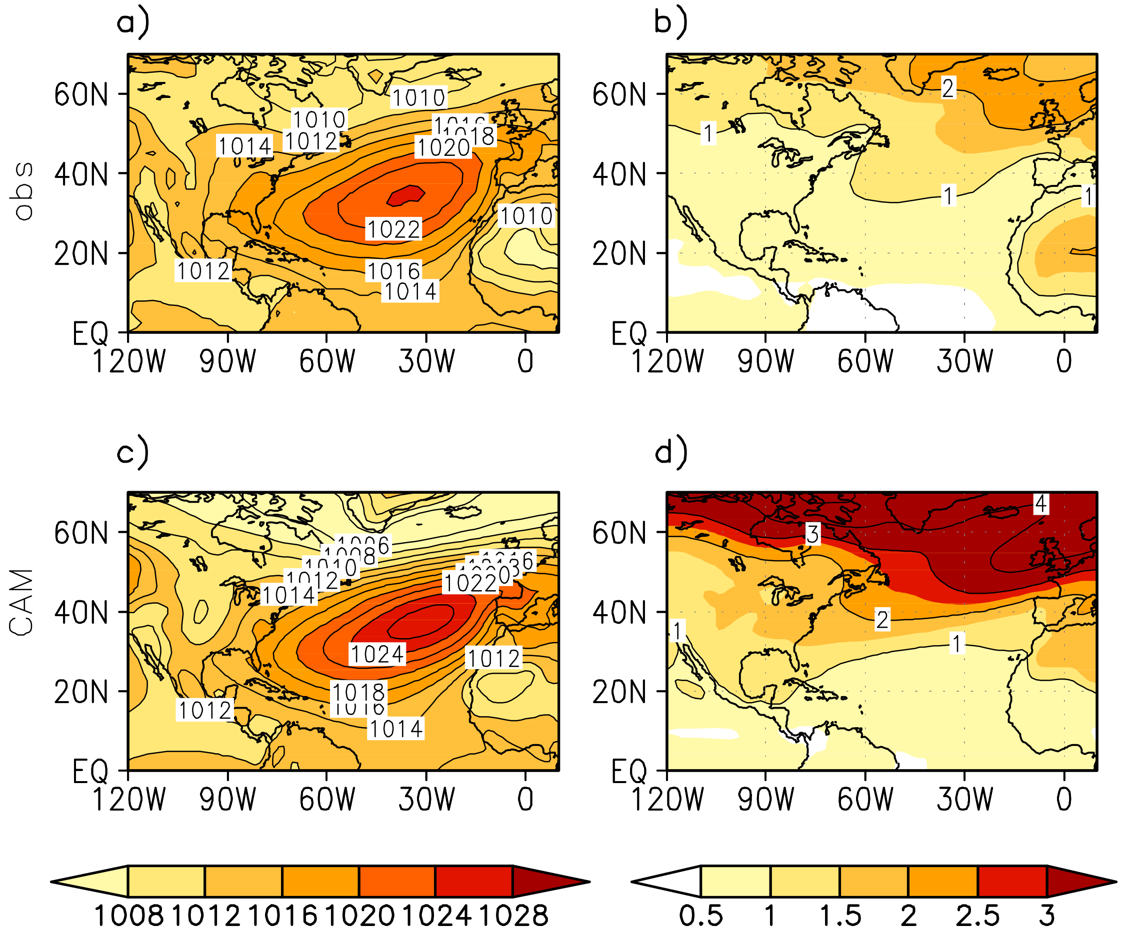

Figure 6. The summer seasonal mean (a and c, Unit: hPa) and standard deviation (b and d, Unit: hPa) of sea level pressure for the period of 1948-2006 from the observation (a and b) and from NCAR CAM3.5 (c and d), respectively.

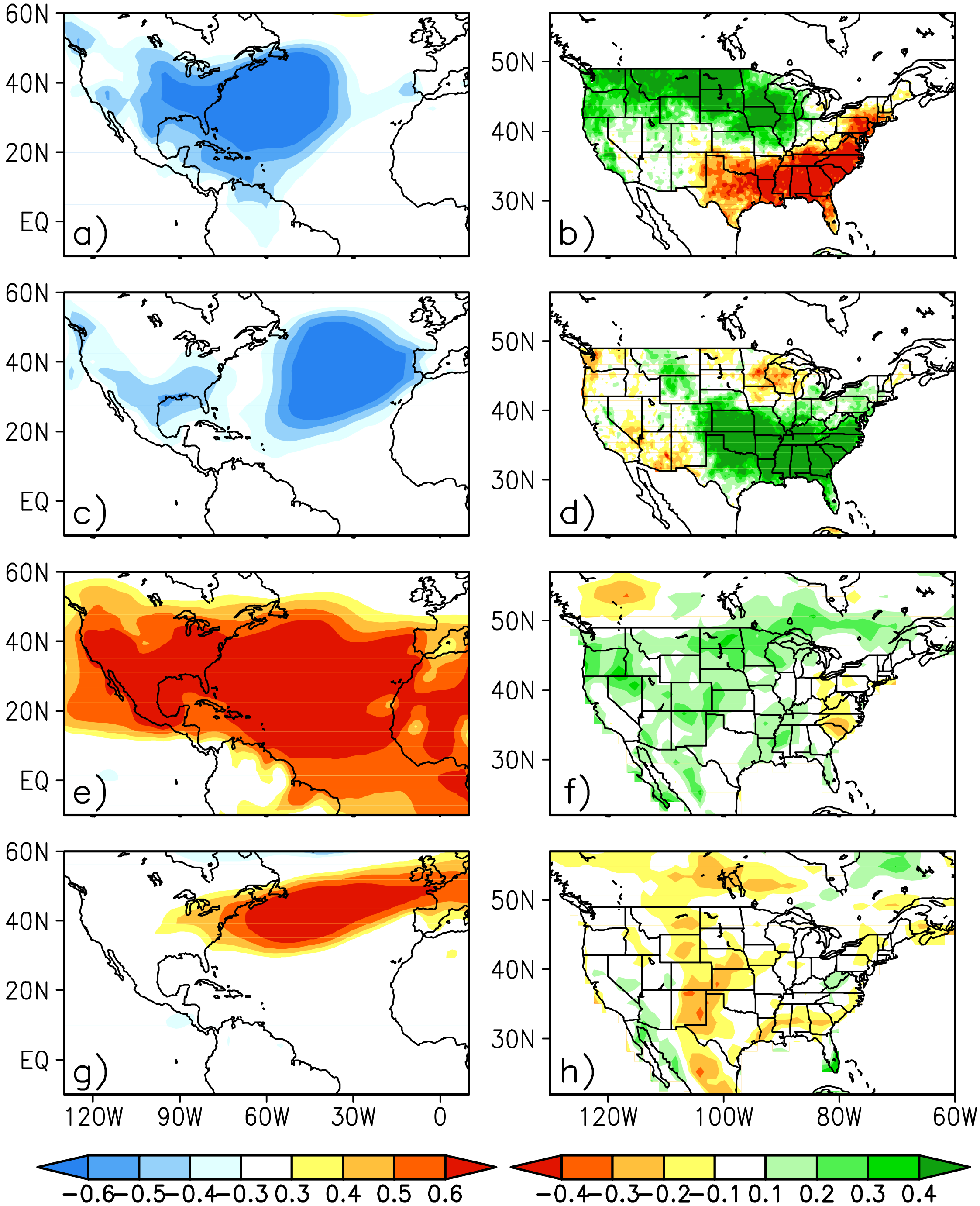

Figure 7. Homogeneous correlation maps of the first (a, b, e, f) and second (c, d, g, h) SVD modes between SLP over the tropical Atlantic and U.S. precipitation from observation (a, b, c, d) and NCAR CAM3.5 model (e, f, g, h). Correlation coefficients exceeding the 95% significance level estimated by the Monte Carlo tests are shaded for left panels; Correlation coefficients greater than 0.2 are significant as estimated by the Monte Carlo tests at 95% (85%) significance level in b) and d) (g) and h)) respectively.

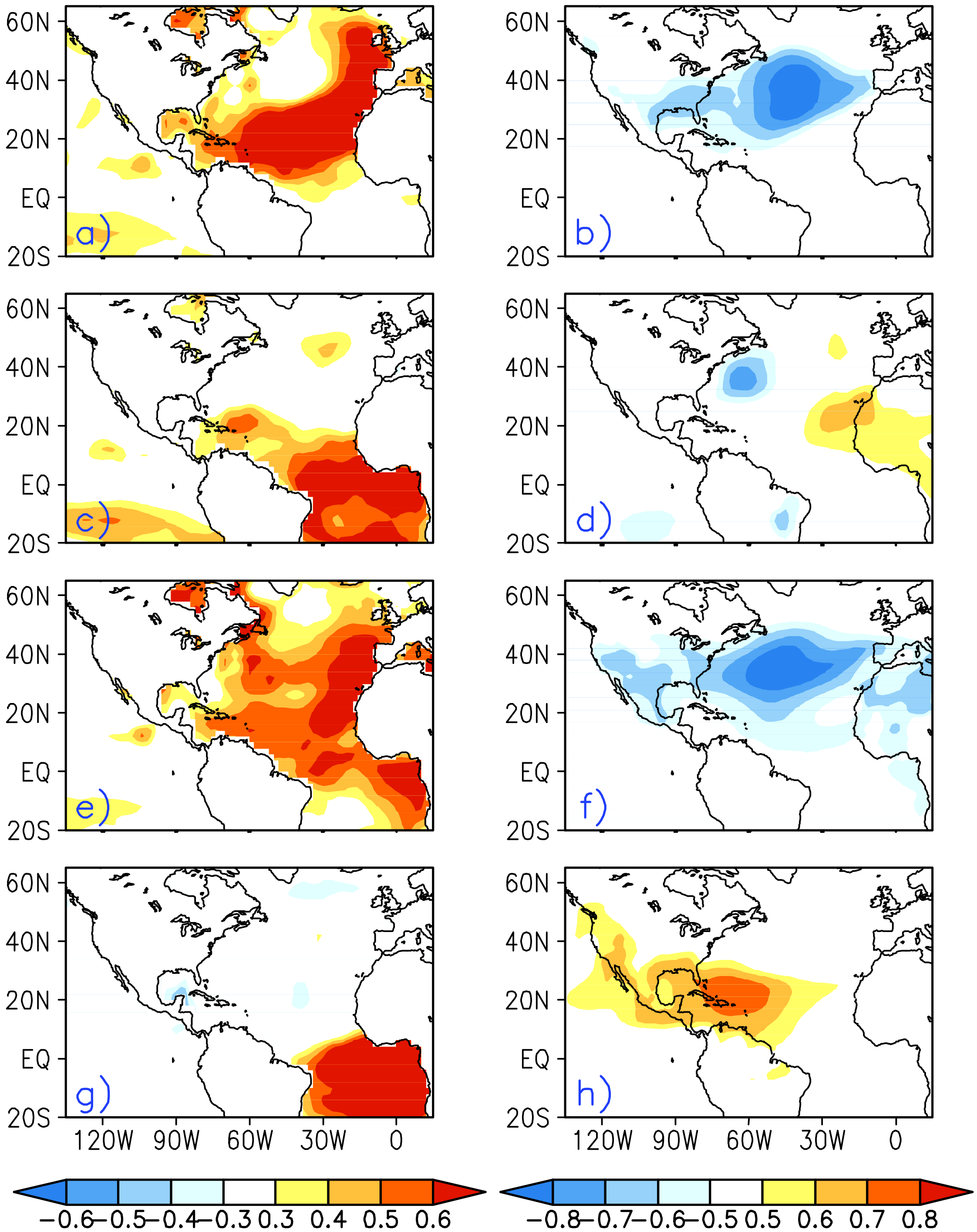

Figure 8. Homogeneous correlation maps of the first (a, b, e, f) and second (c, d, g, h) SVD modes between the tropical Atlantic SST and SLP from the observation (a, b, c, d) and NCAR CAM3.5 (e, f, g, h). Correlation coefficients greater than 0.3 for SST anomalies and 0.5 for SLP anomalies are shaded above 95% significant level as estimated by the Monte Carlo test.