Mechanisms of Tropical Atlantic SST Influence on North American Precipitation Variability

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ABSTRACT

The dynamical mechanisms associated with the impact of year-to-year variability in tropical North Atlantic (TNA) sea surface temperatures (SSTs) on North American precipitation, during the cold and warm halves of the hydrological year (October–September) are examined. Observations indicate that during both seasons warmer-than-normal TNA SSTs are associated with a reduction of precipitation over North America, mainly west of ~90°W, and that the effect can be up to 30% of the year-to-year seasonal precipitation RMS variability. This finding confirms earlier studies with observations and models. During the cold season (October–March) the North American precipitation variability associated with TNA fluctuations is considerably weaker than its association with ENSO. During the warm season (April–September), however, the Atlantic influence, per one standard deviation of SST anomalies, is larger than that of ENSO.

The observed association between TNA SST anomalies and global and North American precipitation and sea level pressure variability is compared with that found in the output of an atmospheric general circulation model (AGCM) forced with observed SST variability, both globally and in the tropical Atlantic alone. The similarity between model output and observations suggests that TNA SST variability is causal. The mechanisms of the “upstream” influence of the Atlantic on North American precipitation are seasonally dependent. In the warm season, warmer-than-normal TNA SSTs induce a local increase in atmospheric convection. This leads to a weakening of the North Atlantic subtropical anticyclone and a reduction in precipitation over the United States and northern Mexico, associated with the anomalous southward flow there. In the cold season, a response similar to the warm season over the subtropical Atlantic is identified, but there is also a concomitant suppression of convection over the equatorial Pacific, which leads to a weakening of the Aleutian low and subsidence over western North America, similar to the impact of La Niña although weaker in amplitude. The impact of TNA SST on tropical convection and the extratropical circulation is examined by a set of idealized experiments with a linear general circulation model forced with the tropical heating field derived from the full AGCM.

1. Introduction

The nature and cause of North American hydroclimate variability is a subject of heightened concern because of the recent droughts1 in the American West2 and in northern Mexico (Seager 2007, 2009) and because projections of anthropogenic influence on the climate of the twenty-first century indicate a turn toward increasing aridity there (Seager et al. 2007). The latter finding, based on output from climate models that participated in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) suggests that droughts such as the present one may become a permanent feature of the region.

Many recent studies examine the interannual and multiyear variability of precipitation and other indicators of drought in North America (e.g., Hoerling and Kumar 2003; Cook et al. 2004; McCabe et al. 2004; Schubert et al. 2004a,b; Acuna-Soto et al. 2005; Seager et al. 2005b). The North American region west of the Mississippi (~90°W) is relatively dry outside of a narrow band along the U.S. West Coast and in the high mountain areas of the northern...
Rocks. Its hydrological state is thus vulnerable to climatic fluctuations on interannual and longer time scales. The climatic history of the region is dotted with long dry periods that have affected the natural environment and human settlement and activities and have had an impact on interstate water-right agreements and policies. Better understanding of the physical-dynamical setting for such events is important for future planning and predictions. The present work is concerned with these aspects as they affect interannual-to-decadal time-scale variability.

Recent modeling studies indicate that the main regulating mechanism of interannual and multiyear variability of precipitation in the American West and northern Mexico, are low-frequency fluctuations in tropical Pacific sea surface temperatures (SSTs). It is well known that tropical Pacific SSTs exhibit large fluctuations with a period of 2–7 yr, which are related to the El Niño–Southern Oscillation (ENSO) phenomenon. These fluctuations neither are symmetric around the mean nor are they regular. Thus, when averaged over a time interval equal to or longer than the ENSO period, they leave a small but dynamically significant residual, either positive or negative, on eastern equatorial Pacific (EEP) SSTs. Evidence that these small anomalies are important to North American climate comes from the work of Schubert et al. (2004a,b) and Seager et al. (2005b). Seager et al. (2005b), in particular, integrated two ensembles of the National Center for Atmospheric Research (NCAR) Community Climate Model 3 (CCM3), both of which were forced with a century and a half (1856–2006) of observed monthly mean SSTs. One ensemble was forced with observed global SST variability, and the other with SSTs prescribed only in the tropical Pacific.3 The two ensembles yielded extremely similar results regarding the variability of rainfall in the American West. Both were in good agreement with the observed record, showing that multiyear droughts in the American West occur when SSTs in the EEP are colder than normal, on average, for several years in a row. The reverse is also true, that is, protracted warming in the EEP leads to a wet interval in the American West (see also Huang et al. 2005). The studies of Schubert et al. (2004a,b) yielded similar results using a different climate model [National Aeronautics and Space Administration’s (NASA’s) Seasonal-to-Interannual Prediction Project model 1 (NSIPP1)]. They demonstrated the importance of the tropical Pacific forcing by comparing the results of ensembles forced with observed global SSTs and several idealized integrations with SSTs prescribed in different ocean basins.

The explanation to the EEP SST impact lies in the response of the atmosphere to ENSO (see Seager et al. 2003, 2005a). In particular, warmer (colder)-than-normal EEP SSTs lead to an overall warming (cooling) of the tropical atmosphere; this causes the maximum in the westerlies to move equatorward (poleward) of its mean position and change the pattern of baroclinic eddy momentum flux convergence in the upper troposphere, thus affecting the mean meridional circulation (MMC). The result is a zonally and hemispherically symmetric anomalous ascent (descent) in the midlatitudes, which in the Northern Hemisphere enhances (suppresses) precipitation in the latitude band of 25°–45°N. In winter, the midlatitude response over North America is enhanced by a stationary wave anomaly caused by the changes in the location of the convective heating centers in the tropics, which forces low (high) pressure in the Gulf of Alaska and ascent (descent) over the American West [a phenomenon known as the Pacific–North American (PNA) pattern; see, e.g., Horel and Wallace (1981), Wallace and Gutzler (1981), and Trenberth et al. (1998)]. Both the zonally symmetric and wavelike response to ENSO thus lead to anomalously wet (dry) winters over North America during El Niño (La Niña) conditions, particularly in the western and southern parts of the country. In the summer, the atmospheric circulation anomalies are weaker, yet similar in phase, and precipitation is probably also affected by changes in the local soil moisture availability, which is carried over from the preceding winter.

As indicated above, the results of Schubert et al. (2004a) and Seager et al. (2005b) suggest that the reason for multiyear drought conditions (and also for persistent wet conditions) lies in cold (warm) SST anomalies that, while smaller in amplitude than their annual counterparts, can affect the state of the climate on decadal time scales (Zhang et al. 1997; Seager et al. 2004; Huang et al. 2005). During the decade-long “Dust Bowl” drought of the 1930s, for example, EEP SSTs were colder than normal, on average, by about 0.2°C, and there was no major El Niño. While there were interannual variations in the strength of this anomaly, the almost-decade-long weak, negative SST anomaly was the leading cause, according to the models, for the drought event.4 However, Schubert et al. (2004b) and Seager et al. (2008) pointed out that during these years North Atlantic SSTs were considerably warmer than normal north of the equator, and they showed

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3 The latter model calculated the SST variability outside of the tropical Pacific by using an entraining ocean mixed layer model, responding locally to the variability of air-sea fluxes and a fixed (calendar month dependent) flux adjustment to climatology (see Seager et al. 2005b for details).

4 Recently, it was shown (Cook et al. 2008) that the dust generated by soil erosion played a secondary yet important role in shaping the location and intensity of the drought.
that the tropical North Atlantic (TNA) warmth was important for the persistence of the drought.

That Atlantic SST variability is associated with, and possibly causes, North American hydroclimate variations, was suggested earlier in the observational studies of Enfield et al. (2001) and McCabe et al. (2004). In the North Atlantic, a multidecadal time-scale “oscillation” of SSTs stands out clearly, even in the temporally unfiltered instrumental record. The phenomenon was referred to as the Atlantic multidecadal oscillation (AMO) by Kerr (2000) and was described earlier by Kushnir (1994) and Schlesinger and Ramankutty (1994). Enfield et al. (2001) argued for the existence of a causal link between the warm phase of the AMO and the relatively warm and dry climate of North America throughout the 30-yr interval of 1931–60, during which the Dust Bowl and the 1950s droughts occurred. After 1960 the Atlantic began to cool and for almost three decades the North American climate turned wetter and colder. McCabe et al. (2004) looked at the association of bidecadal North American drought frequency with both the AMO and its Pacific counterpart, the Pacific decadal oscillation (PDO; Zhang et al. 1997) in twentieth-century observations. Their results supported the conclusions of prior observational studies and are consistent with the recent modeling studies, described in previous paragraphs.

A more recent model study looking at the Atlantic influence on North America hydroclimate was reported by Sutton and Hodson (2005, 2007). These articles provide a detailed analysis of the role of the AMO in precipitation variability around the Atlantic basin. The study consisted of a set of controlled atmospheric general circulation model (AGCM) experiments, using the third climate configuration of the Met Office Unified Model (HadCM3) forced in the North Atlantic with a fixed SST anomaly pattern corresponding to the positive and negative phases of the AMO. The AMO SST anomaly was enhanced by a factor of 4, and each of the two model integrations was carried out for 40 yr, thus providing a robust signal of the atmospheric response. The results show a persistent year-round tropical response that consists of an increase in rainfall in the tropical North Atlantic during a warm AMO phase, combined with reduced rainfall in the eastern tropical Pacific and Indian Oceans. In the American West, significant negative rainfall anomalies occur during the boreal spring and summer when the North Atlantic is warm. Repeating the model integrations, with only the north tropical Atlantic portion of the AMO SST anomaly, yielded similar results in these regions, and differences were found only over the high-latitude North Atlantic. Sutton and Hodson (2005, 2007) concluded that as far as the impact on North American hydroclimate is concerned, it is tropical Atlantic SSTs that are the primary driver.

Most recently, the U.S. Climate Variability and Predictability (CLIVAR) Drought Working Group (DWG) initiated a series of global climate model simulations forced with idealized, fixed (in time) SST anomaly patterns that were prescribed in a different ocean basin. The purpose of this activity was to conduct a comprehensive multimodel study of the mechanisms and impact of global and regional SST forcing on droughts, particularly in the United States, and to investigate the role of land–atmosphere feedbacks. The research methodology was akin to that used by Sutton and Hodson (2005, 2007). However, three different SST patterns were used to force five different AGCMs so that impacts of different ocean basins could be compared and model similarities and discrepancies could be identified. The experimental setting and major results are described in a paper by Schubert et al. (2009, see also more details in section 2). We will later refer to these experiments as they relate to this study.

The goal of the present paper is to add to the existing body of work on the climate processes governing North American hydroclimate by further studying the role of Atlantic SST variability in North American precipitation variability and, in particular, the underlying dynamical mechanisms. Here we use the NCAR CCM3, forcing it with observed time-varying global SSTs (as in Seager et al. 2005b) and with SSTs varying only in the tropical Atlantic basin. In this way we test the sensitivity of prior results (e.g., Sutton and Hodson 2007) to the model and its forcing methodology while maintaining a realistic relation between the SST anomalies (timing and amplitude) and the seasonal cycle. The present experimental methodology also helps to address the role of the Atlantic relative to the Pacific in forcing North American hydroclimate variability. In addition we employ a linear, primitive-equation model to study the underlying dynamical mechanisms.

The plan of the paper is as follows: In section 2 we describe the observational datasets and the modeling methodology used in the study. The results of the analyses of the observations and AGCM output are described in sections 3 and 4, and the linear model results are described in section 5. A summary and discussion are presented in the concluding section.

2. Observations and models

a. Observations

For observations we use a range of available gridded climate analyses. For global precipitation variability, covering both ocean and land regions, we analyze the satellite–gauge blend of the Global Precipitation Climatology Project (GPCP; Huffman et al. 1997). The rather short GPCP record, which extends from 1979 to the present, is supplemented by the National Oceanic and Atmospheric
Administration (NOAA) precipitation reconstruction over land (PREC/L) data (Chen et al. 2002), available since 1948, when examining the observed variations of precipitation over North America in detail. Atmospheric data (specifically, sea level pressure data) are taken from the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis (Kalnay et al. 1996; Kistler et al. 2001). For indices of tropical Pacific and tropical Atlantic SST variability we use the Niño-3.4 index, defined as the SST average in the region lying between 5°S and 5°N and between 170° and 120°W, and the SST average over the tropical North Atlantic between the equator and 30°N (hereafter the TNA SST index). These indices were averaged over the cold and warm months of the hydrological year (October–March and April–September, respectively) and normalized (divided by their RMS value during the relevant period of analysis) when used in the multiple regression analysis calculations described below.

b. Model experiments

This study follows the methodology applied in our previous works, where a relatively large ensemble of AGCM integrations, all forced with the same prescribed SST history but each starting at different initial atmospheric states, is analyzed to determine the response common to all ensemble members. In Seager et al. (2005b) we pursued the hypothesis that decadal equatorial Pacific SST variability is a primary forcing of multiyear droughts in the American West. Three ensembles of the NCAR CCM3 (Kiehl et al. 1998) were integrated for that purpose, each with different SST forcing. Here we use one of these ensembles, consisting of 16 members and forced with observed global SST variability prescribed month by month, from 1856 to the present. This is the Global Ocean (forcing) Global Atmosphere (response; GOGA) experiment. For SST forcing we used a combination of the Lamont optimally smoothed SST dataset (Kaplan et al. 1998) in the tropics and before 1870, and Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST; Rayner et al. 2003) elsewhere.

Along with the GOGA ensemble, and to clearly identifying the Atlantic influence, a new ensemble consisting of 16 members was integrated, using the same climate model but with observed SST variability prescribed only in the tropical Atlantic region, between 30°S and 30°N, leaving climatological conditions elsewhere. Eight such integrations were performed, each starting from different initial conditions. We dubbed this the Tropical Atlantic (forcing) Global Atmosphere (response; TAGA) experiment. In this way the experiment builds on the conclusions of Sutton and Hodson (2005, 2007), who showed that it is tropical Atlantic SST variability that forces North American precipitation changes. Note, however, that Sutton and Hodson focused on the AMO, using a fixed SST pattern, corresponding to the difference between the warm Atlantic years (1930–60) and the cold years (1960–90), enhanced by a factor of 4, while here we prescribe the actual (unenhanced) entire ~150-yr SST history. These two experiments allow the model to vary internally as well as to respond to the prescribed patterns of SST variability globally and in the tropical Atlantic alone. This makes it possible to apply the same analysis methodologies as those applied to the observations, and to compare Pacific and Atlantic impacts.

To support the results obtained in our SST-forced NCAR CCM3 integrations, we present a figure of a multimodel average derived from the output of the Atlantic SST-forced experiments of the U.S. CLIVAR DWG. As indicated above, NCAR’s CCM3 used by our Lamont group was one of the AGCMs participating in the CLIVAR study, as was the NSIPP1 model, the NCEP Global Forecast System (GFS) model, the NCAR Community Atmosphere Model, version 3 (CAM3.5), and the Geophysical Fluid Dynamics Laboratory (GFDL) Atmospheric Model version 2.1 (AM2.1). These models were forced with fixed, idealized SST anomalies in the equatorial Pacific (associated with ENSO), the North Atlantic (resembling the AMO pattern), and globally (associated with the twentieth-century warming trend). The models were integrated for several decades, with the anomalies held fixed at their positive and negative phases as well as with a series of combinations of these idealized anomalies. The difference between the multiyear average of these integrations serves as a measure of the model’s response to a single or combined anomaly forcing [for more information, see Schubert et al. (2009) and http://www.usclivar.org/Organization/drought-wg.html]. Here we briefly compare our present results to the idealized AMO SST-forced DWG results (see section 6).

In addition to the use of a complex, full AGCM, with realistic atmospheric variability, we employ in this study a linear, dry primitive-equation model, to test hypotheses emerging from the analysis of the former. The linear model is an exact linearization of the NOAA/GFDL spectral model with R30 resolution and 14 vertical layers, linearized around a realistic three-dimensional basic state, as in Ting and Yu (1998). In this particular application the model was forced with a three-dimensional heating field between 30°N and 30°S, corresponding to TNA forcing. The heating field was derived from the TAGA ensemble mean by regressing on SST averaged in the tropical North Atlantic Ocean (0°–30°N) region. To suppress high-frequency transients, the model was highly damped. The model was integrated for 50 days, and an average of the last 20 days of the integration is used to represent the stationary response.
3. Observed association between tropical Atlantic SST and North American droughts

a. North American precipitation

Seager et al. (2009) recently studied the relationship between the TNA and Niño-3.4 time series and North American precipitation, by season. They used gridded gauge data from the Universidad Nacional Autónoma de México (UNAM), which covers the United States, Mexico, Central America, and northern South America. Using multiple regression analysis Seager et al. showed that the major effect of both TNA and EEP SST is much more coherent in the cold season (which that study defined as November–April) than in the warm season (defined as May–October). In Fig. 1, we present results of a similar multiple regression analysis applied to the NOAA PREC/L dataset for the years from 1948 to 2007. The precipitation data are averaged by the two halves of the hydrological year and are regressed on the same season Niño-3.4 and TNA indices (see section 2a). The results are consistent with those of Seager et al. (2009, see their Figs. 1 and 2) and with a similar calculation using the shorter GPCP record (Fig. 4 below), indicating the robustness of the main features. Note that a multiple regression on one of the indices amounts to testing its association with the variability in precipitation assuming the other index is held fixed in time.

In the cold season, ENSO’s “influence” (Fig. 1a) is roughly twice as large as that of TNA SST (Fig. 1c). As expected, a cold-season warm equatorial Pacific event (El Niño) is associated with larger-than-normal precipitation over the American West and the U.S. Southeast and over northern Mexico. The anomalies in Fig. 1a amount to up to 60% of the total seasonal RMS variability (not shown). During the same season, warmer-than-normal TNA SSTs are associated with drier-than-normal conditions in most of the same locations, but prominently so over the southwestern U.S. and northwestern Mexico and in the Mississippi River basin and the Great Lakes region. In these regions, anomalies associated with TNA SST variability reach up to 30% of the seasonal precipitation RMS value (not shown). If this association is forced by TNA SST variability, it indicates a competition between the Pacific and the Atlantic influences on North American precipitation. That is because during the cold season, ENSO forces the same-sign SST anomaly in the tropical Atlantic (e.g., Enfield and Mayer 1997). Thus, a Pacific warm (cold) event forces an increase (decrease) in North American precipitation, and at the same time induces a warming (cooling) of the TNA region, which affects precipitation in the opposite manner [i.e., a weakening (strengthening) of precipitation] in much of the same regions. This competition is obviously won by the Pacific, but the overall effect is a weaker ENSO influence. Notably, however, TNA SSTs display variability independent of ENSO (e.g., Czaja et al. 2002), which could, at times, work in consort with ENSO to increase the overall impact on North American precipitation, and vice versa.

The association of the Mississippi River basin and the Great Lakes region precipitation variability with Atlantic SST fluctuations is consistent with the studies that looked at the long-term impact of the Atlantic Ocean on North American precipitation (e.g., Enfield et al. 2001; McCabe et al. 2004).

The warm-season anomalies associated with TNA SSTs (Fig. 1d) are similar to their cold-season counterparts but are somewhat less extensive (Fig. 1c). Drying associated with warm TNA SST anomalies is found in the American Southwest and in northern Mexico, with a secondary maximum in the Great Lakes region. Note also that the impact of the Atlantic during the summer is stronger than that of ENSO (Fig. 1b). (Confirmation of these observational results from a different dataset, covering a shorter period, can be found in Fig. 4 below.)

b. Global patterns

The global SLP and precipitation patterns associated with tropical Pacific and tropical Atlantic SST variability were derived in a similar manner, using multiple regressions on the Niño-3.4 and TNA SST normalized indices. The analysis is confined to the years from 1979 to 2007 to match the satellite record, which provides precipitation estimates over the oceans. Figure 2 presents only the TNA-related multiple regression patterns. The Niño-3.4 regression patterns (not shown) display the well-known, extensive tropical Pacific precipitation anomalies and the weaker ones forced over other parts of the world. In SLP, there is a negative cold-season anomaly over the North Pacific and the eastern tropical Pacific, which is related to the response to anomalous tropical convective activity associated with ENSO (e.g., Trenberth et al. 1998; Seager et al. 2005a). A similar but weaker pattern is seen in the warm-season months.

The cold-season SLP regression on TNA SST (Fig. 2a) displays a dipole pattern over the North Atlantic, which resembles the North Atlantic Oscillation (NAO). The sense of the relationship is such that warmer-than-normal TNA SSTs are associated with a negative NAO state. This is consistent with the notion that a negative NAO forces warm SSTs over the subpolar and TNA regions (Seager et al. 2000; Hurrell et al. 2003) and is therefore, most likely, the cause of (and not the response to) the TNA SST change. However, as we shall see below, the model results indicate that the subtropical low pressure anomaly may also include a forced response to the warm TNA SST.
Over the North Pacific and North America, the cold-season SLP pattern associated with a warm TNA SST anomaly (Fig. 2a) displays a pattern that resembles the negative phase of the PNA teleconnection pattern, associated with (and forced by) cold EEP SST anomalies (Horel and Wallace 1981). Note that the association seen in Fig. 2a is in opposite polarity to that which would be expected if the TNA SST anomaly were forced by ENSO. If that were the case, we would expect to find, associated with a negative PNA, cold SST anomalies in the TNA region (Enfield and Mayer 1997), while the pattern in Fig. 2a corresponds to warm TNA SSTs. Thus, the multiple regression analysis points at a Pacific response that is most likely forced from the TNA or that both the TNA and the North Pacific are forced by a third “party” not associated with ENSO (see further discussion below). Together, the North Atlantic and North Pacific SLP anomalies of Fig. 2a indicate a southward flow over the American West, which should be associated with dynamically driven subsidence and hence with a negative precipitation anomaly in the region [see discussion of the stationary response to El Niño in Seager et al. (2005a)].

The Pacific sector SLP anomalies in Fig. 2a are symmetric about the equator, with the high pressure anomalies over the eastern North Pacific paralleled by an anomaly of the same sign in the South Pacific. This hemispheric symmetry is consistent with tropical forcing. An examination of the precipitation anomaly field indicates that the mid-latitude anticyclone pair in the middle of the Pacific basin straddles a negative precipitation anomaly situated in the central tropical Pacific and is flanked by positive anomalies to the west and east. As we shall argue below, based on results from a hierarchy of global models, this weak “La Niña-like” arrangement in the Pacific basin is forced remotely by increased convection over the warm TNA SST.

The warm-season SLP pattern associated with TNA SST (Fig. 2b) is, to some extent, a weaker expression of that of the cold season. Here too we find enhanced precipitation over the western TNA and a low pressure anomaly over the subtropical North Atlantic. Over North America, precipitation is reduced. In the Pacific, precipitation increases...
west of 150°W but mainly over the Maritime Continent and the Indian Ocean. This is associated with a subtropical anticyclonic pair straddling the equator in the western Pacific and negative subtropical precipitation anomalies.

We note that because of the short record of satellite-based precipitation estimates, these results should be viewed with caution. However, we did confirm that the main SLP features in Fig. 2 are reproducible by repeating the multiple regression analysis with a longer reanalysis record and with the century-long Hadley Centre Sea Level Pressure (HadSLP) dataset (not shown). Also important to note is that regression analysis does not indicate that TNA SST variability is forcing the observed changes. It is possible that the changes in the global SLP pattern, in particular, are forced from other ocean regions that tend to vary in phase with TNA SST. During 1979–2007, TNA SST exhibited a warming trend that explains ~6.25% of its seasonal variance. This trend is consistent with the warming trend in other tropical ocean regions, particularly the Indian Ocean and the South Atlantic. We chose not to remove the trend from the observed TNA SST time series because it could be, in part, attributable...
to the AMO (see Ting et al. 2009). Moreover, we are interested here in the impact of TNA SST warming regardless of its cause. The disadvantage of this approach is that it is possible that the changes in the Pacific circulation, in particular, are partially linked to the SST trend in other ocean regions. In the next sections we compare the observed patterns with the AGCM results, forced only with TNA SST variability, which by their similarity to their observed counterparts add further credence to the role of the TNA in forcing the changes in circulation described above.

4. AGCM results

Figure 3 displays the results of a multiple regression analysis applied to the GOGA and TAGA ensemble-mean output (note that with TAGA the multiple regression reduces to a simple linear regression with the TNA index). Both the global SLP and precipitation fields are analyzed following the same procedure applied to the observations in Fig. 2. Here too, only the regression patterns corresponding to TNA SSTs are shown. The analysis is performed over the same time interval used for the observations (1979–2007) for better comparison. The resemblance to observations (Fig. 2) is striking, considering that Fig. 2 is derived based on the (single) observed realization, while the model results are based on an ensemble average of 16 GOGA and TAGA independent realizations, forced with the same SST conditions. Ensemble averaging strongly reduces the variability that is not related to the prescribed SSTs, and thus the fields should be less “noisy.” In addition, we should consider the fact that the observed relationship includes atmospheric variability that could have caused the TNA SST anomalies (such as the NAO), and not only the response to the latter. In the AGCM, the atmospheric variability that is unrelated to the prescribed SSTs has no influence on the state of the ocean and thus has been averaged out. The model results, however, may include spurious features that are unphysical, such as the tendency to precipitate excessively (compared to observations) over areas with prescribed warmer-than-normal SSTs. In areas where the anomalous SSTs are related to increased insolation because of reduced clouds and precipitation, the model precipitation response is unrealistic. We will return to this issue below in discussing the model precipitation response to TNA SSTs.

The model SLP regression patterns confirm that over the TNA, the circulation responds to SST variability in both cold and warm seasons by increased convection activity and a weak, albeit significant, low pressure anomaly. In the cold season (Figs. 3a,c) the model displays a low pressure anomaly over the entire North Atlantic basin, in contrast with the observations, where a large, positive anomaly is centered just east of Greenland (Fig. 2a). As discussed above, the observed pattern mainly reflects the NAO forcing of TNA SST variability (e.g., Seager et al. 2000). The model results indicate, however, that TNA SST anomalies can force a weakening of the Atlantic subtropical anticyclone with consequences to North American precipitation. This positive feedback response from TNA SSTs (in the case of NAO forcing) was mentioned in earlier studies (e.g., Terray and Cassou 2002; Peng et al. 2005). The simulated high pressure anomaly over the Gulf of Alaska and the North Pacific is more robust than in observations and is much stronger (and more so in GOGA than in TAGA; see more below). Circulation features over the South Pacific are weaker than those in the observations but are consistent in phase (missing is the noisy pattern over Antarctica, which in observations can be attributed to the short record and to deficiencies in the reanalysis output over this data-sparse region). In the warm season (Figs. 2b and 3b,d), the agreement is in the low pressure anomaly over the TNA region as well as the anomaly centers over the Pacific, both north and south of the equator, although here the North Pacific anticyclonic anomaly is weak.

The layout of tropical precipitation anomalies in the GOGA (Figs. 3a,b) and TAGA (Figs. 3c,d) is similar to the observed features discussed in section 2. A more detailed comparison of the TNA-related observed and modeled precipitation anomalies over the tropical Atlantic and the Americas is shown in Fig. 4. GOGA (Figs. 4b,c) and TAGA (Figs. 4e,f) exhibit significant positive precipitation anomalies over the TNA region, extending from the West African seaboard to the Caribbean and Central America. The pattern resembles the layout of the summertime ITCZ and corresponds to its intensification resulting from warmer TNA SSTs. We are not the first to note that there is a positive correlation between TNA SSTs and precipitation in that region. Refer, for example, to Ruiz-Barradas et al. (2000) or Chiang and Vimont (2004) for analyses based on the estimated satellite precipitation and to Seager et al. (2009) and Giannini et al. (2001) for analyses based on a longer regional station record. However, in the model experiments, particularly the TAGA runs, these positive precipitation anomalies are much stronger than those in the observations (cf. Figs. 4a,b). This could be due to the ensemble averaging (which removes features that are not related to the prescribed SSTs) and/or to the fact that AGCMs with prescribed SSTs are known to display an excessive convective response to prescribed warm anomalies (e.g., Biasutti et al. 2006).

Figure 4 implies that the model response, while exaggerated, is not unrealistic, and that convection in the TNA region is positively correlated with underlying SSTs. Particularly noteworthy is the similarity in the
wintertime pattern of the positive precipitation response over the Caribbean Sea and into the eastern Pacific, where the focal point of the SST-forced response is located. Note also the general similarity in the impact over North America to which we refer again below. The model precipitation anomalies in the central equatorial Pacific (Fig. 3) are generally negative, reaching ~1 mm day$^{-1}$ in the center of the basin during the cold season (Fig. 3a).

There are some notable differences between the TAGA and GOGA responses to TNA SST anomalies (Fig. 3). In TAGA (Figs. 3c,d), the precipitation anomalies over the tropical Pacific are weaker and less coherent compared to GOGA (Figs. 3a,b) and the SLP anomaly in the Gulf of Alaska during winter is also weaker. In the Atlantic, however, the low pressure anomaly over the northern ocean basin is stronger. Also noticeable in TAGA is a large negative precipitation response over the tropical Indian Ocean, particularly during the warm season, when the anomaly over the Bay of Bengal reaches ~1 mm day$^{-1}$. In the observations (Fig. 2) and in GOGA there are positive precipitation anomalies there. We attribute the difference to the specification of climatological SST conditions in the Indian Ocean in TAGA, while in GOGA SST they vary realistically. Observed SST variability in the tropical Indian Ocean exhibits considerable coherence with TNA SST variability, mainly due to the gradual warming of most of the tropics, excluding the EEP, during the twentieth century. This warming trend could have lead to the increased convection over the Indian Ocean (as seen in GOGA). Furthermore, increased Indian Ocean convection could also lead to a remote effect in the North Pacific, specifically the Gulf of Alaska (see Hoerling and Kumar 2003; Hoerling et al. 2004), and thus explain the stronger wintertime North Pacific response in GOGA compared to TAGA (Figs. 3a,c).

Figure 4 provides a comparison between the simulated and observed seasonal change in North American precipitation associated with TNA SST. Concerning these continental patterns, we note first that the observed anomalies during 1979–2007 (Figs. 4a,b) compare quite well with their counterparts during the 60-yr period used in Fig. 1. We also find that the model ensembles (Figs. 4c–f) display a rather
successful simulation during both winter and summer months. Notably, the TAGA response (Figs. 4e,f) is stronger than that of GOGA (Figs. 4c,d). This seems consistent with the stronger convection response in TAGA over the TNA region.

5. Linear model results

As described in section 2, the linear model was forced with the tropical-band, three-dimensional diabatic heating field, which was derived by regressing the TAGA ensemble-mean field on the TNA SST index, by season. We chose the TAGA output to demonstrate most clearly the role that tropical Atlantic SST variability can play in North American precipitation variability. Our intention is to isolate the role of TNA SST-driven diabatic heating alone, and not to create the best simulation of the observations or the AGCMs by using a linear model. We wanted to study the response to the heating confined to the region of specified SSTs but also to explore the hypothesis put forward above that during winter, TNA SSTs exert a remote impact on the tropical Pacific convection with implications for North America. When forcing the linear model, the imposed heating was limited to the latitude belt of 30°S–30°N. The linear model was integrated with full tropical heating, the TNA part of the heating (specified between 100°W and 0°), and the Pacific part of the heating (specified as 110°E–100°W) separately. The results shown below are not very sensitive to the exact choice of these latitude–longitude boundaries.

The horizontal pattern of the vertically averaged TNA-regressed TAGA heating (not shown) mimics, as expected, the pattern of the precipitation anomaly shown in Figs. 3c,d. The anomaly varies somewhat by season, with
a year-round enhancement of diabatic heating in the TNA region and a suppression of tropical Pacific heating around the date line. Figure 5 shows the vertical structure of the TAGA heating regressed on the TNA index and averaged between 20°S and 20°N, where the largest precipitation anomalies are located. The figure displays a positive heating anomaly over the tropical Atlantic basin, associated with increased convection there and elevated anomalous cooling almost everywhere else. The cooling is associated with the suppressed convection over the Pacific and Indian Ocean basins. There is weak warming in a shallow layer in the lower troposphere in the tropical Pacific. However, the elevated cooling is the most likely feature to affect the extratropical regions, as evident from the forced linear model results discussed below. The seasonal differences are small and are mainly associated with a stronger tropical Atlantic signal in the warm season. A multiple regression of the GOGA heating field on the TNA SST index (not shown) yields qualitatively similar results except for the Indian Ocean region, where the signal is weakly positive, consistent with the precipitation field in Fig. 3.

Figure 6 displays the lower- and upper-tropospheric warm-season streamfunction response of the linear model to the all-tropics heating. The full TAGA AGCM streamfunction regressions on TNA SST are shown for
comparison in the top two panels. Over the Atlantic and the Americas, the TAGA warm-season response to SST imposed in the tropical Atlantic (Figs. 6a,b) is consistent with the “Gill response” to tropical heating (Gill 1980; Jin and Hoskins 1995; Ting and Yu 1998). With TNA heating only (not shown) the response over the Atlantic and the Americas is similar, confirming that the “chain of events” in summer is that warm SST anomalies in the TNA region lead to increased convection, mainly in the core of the Atlantic ITCZ region, which forces a pair of low-level cyclonic circulation anomalies straddling the heating center. Aloft, there is a pair of anticyclones. The linear model response confirms that effect of the Caribbean-centered low-level anomalous cyclone over the American West and northern Mexico is to induce an anomalous subsiding southward flow and a negative precipitation anomaly (not shown). What seems to be unrelated to Atlantic heating is the large lower-tropospheric response over the Indian Ocean, which is simulated by the linear models only when the entire tropical heating pattern is enforced and is thus related to local SST forcing. The impact of Pacific heating alone on the summer circulation is negligible (not shown).

In the observations and the AGCM used here, the tropical Atlantic is also responsible for reduced precipitation over North America in winter. We suggested earlier that the winter drying is associated with a more complex dynamical response to TNA SSTs than that found in summer. This cold-season response is studied further in Fig. 7. Outside of the immediate vicinity of the heating maximum, in the TNA region the response is equivalent barotropic (not shown), which is consistent with theory (see Hoskins and Karoly 1981). Thus, the midtropospheric streamfunction response in Fig. 7 is chosen to represents a troposphere-deep pattern in both the North Pacific and the North Atlantic. Only within the TNA region is the response baroclinic (as anticipated from a heating-forced response), with a high pressure anomaly in the upper troposphere overlying a local low-level low pressure anomaly (not shown).

To reproduce close to the full strength and detailed response of the cold-season atmosphere to TNA SST, the linear model had to be forced by the full tropical heating field (cf. Figs. 7a,b; the small discrepancies in the strength of the response pattern can be attributed to the absence of transients and/or extratropical heating in the linear

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**FIG. 6.** (left) The TAGA warm-season streamfunction regression on the TNA SST index at the sigma level of (a) 0.866 and (b) 0.17. (right) The linear model streamfunction response to tropical heating at (c),(d) the same model levels, respectively. Contour interval is (a),(c) 2 and (b),(d) 10. Units are 10^5 m^2 s^{-1}. Negative contours (dashed) and the zero contours (heavy black lines) are shown. Shading is added to emphasize the main features.
With the Atlantic portion of the heating alone, the model responds most strongly (but with a lower amplitude than the full heating field) over the North Atlantic (Fig. 7c), and with Pacific heating alone the model responds mainly over the North Pacific (Fig. 7d). The tropical Pacific suppressed convection response to the warm Atlantic SST (Fig. 5) is thus important for explaining the high pressure (and La Niña like) response over the North Pacific. The linear model shows that broad, continental-scale subsidence over the United States is associated with the TNA-only forcing and that the Pacific heating response is enhancing this subsidence over the American Southwest and northern Mexico (not shown).

We argued above that warm TNA SST anomalies force the diabatic cooling response in the rest of the tropics, as seen in Fig. 5. Indeed, an examination of the TAGA tropical vertical motion field reveals broad areas of subsidence consistent with the regions of diabatic cooling in Fig. 5 (not shown). However, in the full GCM this pattern of vertical motion cannot be viewed separately from the suppressed convection, and thus it may not be causal. To explore the forced vertical motion response to tropical Atlantic SST alone we turn to the linear model experiment with the heating imposed only over the TNA region. Figure 8a displays the average linear model vertical motion response to TNA heating. Over the tropical Atlantic we find the expected upward motion associated with the heating; elsewhere the model displays weak subsidence.

The subsidence seen in Fig. 8a is tied to the horizontal spreading of high-level warming by equatorial waves (Kelvin and Rossby waves) and the associated stabilization of the tropical atmosphere outside of the immediate region of increased convection. Yulaeva and Wallace (1994) demonstrated the existence of such a mechanism accompanying ENSO. Recently, Chiang and Sobel (2002) invoked this mechanism to explain the tropical convection and SST response to ENSO variability outside of the tropical Pacific. As seen in Fig. 8b, the tropospheric high-level tropics-wide warming is a linear stationary response to the heating prescribed over the tropical Atlantic. The combined effect of the stabilization of the atmosphere and the associated subsidence over the equatorial Pacific are therefore the result of the increase convection over the TNA region. The tropical temperature response in the full TAGA ensemble (Fig. 9) displays a strong warming signal over the TNA but a weak cooling over the tropical Pacific that is deep in winter (Fig. 9a) and shallow in summer (Fig. 9b). This pattern obviously reflects the equilibrated response to the
remote influence of the Atlantic, which includes the effect of the forced reduction in convective heating over the Pacific.

6. Summary and discussion

Observations and model studies indicate that changes in SST on interannual and longer time scales in the tropical North Atlantic affect the precipitation in North and Central America. Positive SST anomalies in the TNA region are associated with negative precipitation anomalies (and droughts) over most of the contiguous United States, particularly in the West (Figs. 1 and 2) and over Mexico. This is the case in both halves of the hydrological year—October through March and April through September—with a somewhat larger effect in the cold half of the year. In experiments with an AGCM forced with the observed history of SST variability, the association between TNA SST variability and North American precipitation is reasonably well simulated (Fig. 4). Overall, the model results indicate that TNA SST variability is forcing North American precipitation.

During the cold season, the change in precipitation associated with one standard deviation of TNA SSTS is considerably smaller than the change associated with the normalized Niño-3.4 index, but in summer the Atlantic influence is larger (Fig. 1). On interannual time scales, the standard deviation of EEP SSTs is considerably larger than that of TNA SSTs. Thus, tropical Pacific SST fluctuations should dominate the variability of precipitation in North and Central America when year-to-year changes are concerned. However, on decadal and multidecadal time scales, SST variability in both ocean regions is comparable and the Atlantic influence should become more important, particularly so in the warm season. Moreover, the Atlantic influence is realized year-round, thus reducing the likelihood for soil moisture recharge during multyear droughts.

The interplay between the Pacific and Atlantic effects on North American hydroclimate can be discerned in Fig. 10. The figure displays a long time series of an indicator of North American hydroclimate, along with the low-frequency variations of Niño-3.4 and the TNA SST indices. The hydroclimate indicator is the tree-ring-based
estimate of the annual Palmer Drought Severity Index (PDSI) taken from the North American Drought Atlas (NADA; Cook et al. 2004). NADA provides a temporally stable fit to the observations in the recent past and a regression-based extrapolation to the preinstrumental era (which, in some location, covers the last two millennia). Here we use the NADA from 1856 to the present and display the average over the American West (25°–50°N, 125°–90°W). Figure 10 exhibits a systematic relationship between North American hydroclimate variability and EEP SST fluctuations. In particular, we note that on decadal time scales, the PDSI time series follows the Niño-3.4 fluctuation. However, Fig. 10 also indicates that the American West is subjected to more severe droughts when the TNA is warmer than normal, compared to when it is colder than normal. In particular, the Dust Bowl, the 1950s drought, and the recent turn-of-the-century drought (Seager et al. 2007) occurred during cold equatorial Pacific events and an extended interval of warm TNA SSTs. In contrast, cold events in the Pacific did not affect the American West as severely when the TNA was in a cold state (e.g., around 1910 or in the mid-1970s).

During the short interval corresponding to the era of satellite observations, the Atlantic-related precipitation variability in North America is associated with dynamically consistent features surrounding North America over the Atlantic and Pacific Ocean basins. Positive TNA SST anomalies in both halves of the hydrological year are associated with a local increase in precipitation and a weakening of the Atlantic subtropical anticyclone (Fig. 2). A comparison with the output of the SST-forced AGCMs (Fig. 3) indicates that these features are robust and that the change in subtropical Atlantic precipitation can be attributed to the change in SST (Fig. 4). In the cold half of the hydrological year a consistent string of changes over the Pacific, in both the observations and model simulations, are found accompanying the TNA SST variability. The tropical rainfall field displays a negative anomaly in the central equatorial Pacific, which is straddled by positive SLP anomalies in the extratropics of both hemispheres (Figs. 2 and 3).

Considering the similarity between the model simulations and the observations, we argue that warmer-than-normal SST anomalies in the tropical Atlantic during the warm season lead to increased convection there, and that this forces a “Gill type” response that weakens the subtropical North Atlantic anticyclone. The resulting influence over North America is an anomalous southward flow and cold advection in the low troposphere. This leads to anomalous subsidence, via the heat and vorticity balances, over the American West, as well as reduced moisture flux convergence, and hence a suppression of rainfall. This hypothesis is confirmed with a linear AGCM forced with the tropical heating field associated with TNA SST anomalies in the full AGCM. The linear model results show that the TNA portion of the tropical heating field alone can explain the circulation response in both seasons.

In the cold season the TNA heating anomalies alone cannot explain the complex circulation features, which include an upstream impact on the North Pacific. Here
we argue that increased convection in the TNA region, related to warm SSTs, leads to the suppression of convection over the central tropical Pacific. This is due to subsidence and increased tropical static stability forced from the tropical Atlantic through the tropical waveguide. The suppression of normal convective activity in the tropical Pacific forces a positive North Pacific pressure anomaly (a weakening of the seasonal Aleutian low), which is an atmospheric response that exacerbates the suppression of precipitation over the American West resulting from the Atlantic impact alone. It is worth noting that the influence of a TNA SST warming during the cold season on the North Pacific atmospheric circulation and American West precipitation yields a pattern that is similar to that of a typical La Niña event, though it is much weaker in magnitude. This is why a combination of a cold tropical Pacific (La Niña) and a warm tropical North Atlantic (cf., the negative phase of the AMO) cause the most severe dry conditions over the western North America. Interestingly, a recent article by Okumura et al.
experiments also suggest that the influence of the Atlantic response to SST-induced heating in the TNA region, these
studies and models. In addition to confirming the Gill-type
anomalies and TNA SSTs, seen previously in observa-
tional ground the association between U.S. precipitation is as much or even more important than in the
United States and northern Mexico where winter pre-
2007). This is important particularly in the Southwest
basins. In addition, there is a substantial low pressure re-
sponse in the North Pacific, which is quite similar to that
seen in the TAGA and GOGA integrations. The Okumura
et al. study shows that the change in North Pacific SLP (and geopotential height) is due to the cooling of the TNA re-
region and the related impact on the tropical Pacific.

It is interesting to compare the results of our study to
those obtained in the idealized set of experiments taken
up by the U.S. CLIVAR DWG (see section 2b). The
“consensus” AGCM precipitation and precipitation and SLP response to a typical AMO SST change (positive–
negative experiments), shown in Fig. 11, is entirely con-
sistent with the findings in this study (cf. Figs. 3c,d), despite
the different methodology (prescribed fixed versus time-
varying SSTs and the domain covered by the prescribed anomalies) and the additional models used in these com-
posites. It confirms the existence of a local Atlantic basin
response to a warming of Atlantic SST, as well as a remote
Pacific response associated with the suppression of tropical
Pacific convection.

The present study thus confirms previous work that
proposed, based on observations and models, that At-
lantic SST variability, particularly in the TNA region, influences seasonal and annual precipitation variability in parts of North and Central America (e.g., Enfield et al. 2001; McCabe et al. 2004; Schubert et al. 2004b; Sutton and Hodson 2005, 2007; Seager et al. 2008, 2009).

Our paper emphasizes that the Atlantic impact is felt
on interannual time scales and not necessarily just on
multidecadal scales, as emphasized by some on the pre-
vious studies. While the impact of the Atlantic is rela-
tively weak compared to that of ENSO during winter, it is
felt year-round and not only in summer as suggested,
e.g., by Enfield et al. (2001) or Sutton and Hodson (2005,
2007). This is important particularly in the Southwest
United States and northern Mexico where winter pre-
2005 to 2007). This period was chosen to include the
so-called North Atlantic Oscillation (NAO) dipole, which is
a common feature of the NAO in recent decades. More
recently, the North Atlantic has been characterized by
an enhanced positive NAO phase (i.e., a strong warm
and dry period over Europe and a cold and wet period
over North America), which is known to influence the
climate of the North Atlantic and the North Pacific.

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