# Is there an optimal ENSO pattern that enhances large-scale atmospheric processes conducive to major tornado outbreaks in the U.S.?

Sang-Ki Lee[1,2], Robert Atlas[2], David Enfield[1,2], Hailong Liu[1,2], Chunzai Wang[2], and Brian Mapes[3]

[1]Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, Florida, USA

[2]Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami Florida, USA USA

[3]Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA

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Corresponding author address: Dr. Sang-Ki Lee, NOAA/AOML, 4301 Rickenbacker Causeway, Miami, FL 33149, USA. E-mail: Sang-Ki.Lee@noaa.gov.

**Abstract**

Observations and modeling experiments are used to show that a positive phase of Trans-Niño, characterized by cooling in the central tropical Pacific and warming in the eastern tropical Pacific, is linked to an increased number of intense U.S. tornadoes in spring. The warming in the eastern tropical Pacific increases convection locally, but also contributes to suppressing convection in the central tropical Pacific. This in turn works constructively with cooling in the central tropical Pacific to force a strong and persistent negative phase Pacific – North American (PNA)-like teleconnection pattern in spring that increases both the upper-level westerly and lower-level southeasterly over the central and eastern U.S. These anomalous winds bring more cold and dry upper-level air from the high-latitudes and more warm and moist lower-level air from the Gulf of Mexico converging into the U.S. east of the Rocky Mountains, and also increase the lower-level vertical wind shear therein, thus providing large-scale atmospheric conditions conducive to intense tornado outbreaks over the U.S. A distinctive feature in the 2011 Trans-Niño event is warming in the western tropical Pacific that further aided to suppress convection in the central tropical Pacific and thus contributed to strengthening the teleconnection response in the central and eastern U.S. in favor of increased U.S. tornado activity.

## 1. Introduction

In April and May of 2011, a record breaking 1,243 tornadoes were reported in the United States (preliminary estimate). This resulted in 517 tornado-related fatalities, making 2011 one of the deadliest tornado years in U.S. history [http://www.spc.noaa.gov/climo/torn/fataltorn.html]. Questions were raised almost immediately as to whether the series of extreme tornado outbreaks in 2011 could be linked to long-term climate variability. The severe weather database (SWD) from the National Oceanic and Atmospheric Administration indicates that the number of total U.S. tornadoes (i.e., from F0 to F5 in the Fujita-Pearson scale) during the most active tornado months of April and May (AM) has been steadily increasing since 1950 (Figure S1a). However, due to numerous known deficiencies in the SWD, including improvements in tornado detection technology and changes in damage survey procedure over time, one must be cautious in attributing this secular increase in the number of U.S. tornadoes to a specific long-term climate signal [Brooks and Doswell 2001; Verbout et al. 2006]. Since intense and long-lived tornadoes are much more likely to be detected and reported even before a national network of Doppler radar was build in the 1990s, the number of intense U.S. tornadoes (i.e., from F3 to F5 in the Fujita-Pearson scale) in AM during 1950-2010 is obtained from the SWD (Figure S1b) and used, after detrending, as the primary diagnostic index in this study (Figure S1c). A simple least squares linear regression is used to detrend the number of intense U.S. tornadoes in this study.

In the U.S. east of the Rocky Mountains, cold and dry upper-level air from the high latitudes often converges with warm and moist lower-level air coming from the Gulf of Mexico (GoM). Due to this so-called large-scale differential advection (i.e., any vertical variation of the horizontal advection of heat and moisture that decreases the vertical stability of the air column [Whitney and Miller, 1956]), conditionally unstable atmosphere with high convective available potential energy is formed. Additionally, the lower-level vertical wind shear associated with the upper-level westerly and lower-level southeasterly (i.e., wind speed increasing and wind direction changing with height) provides the spinning effect required to form a horizontal vortex tube. The axis of this horizontal vortex tube can be tilted to the vertical by updrafts and downdrafts to form an intense rotating thunderstorm known as a supercell, which is the storm type most apt to spawn intense tornadoes [e.g., Doswell and Bosart, 2001]. Consistently, both the moisture transport from the GoM to the U.S. and the lower-level vertical wind shear in the central and eastern U.S. are positively correlated (above 95% significance level) with the number of intense U.S. tornadoes in AM (see Table 1). See Brooks et al. [2003] for various other meteorological indices used to estimate the occurrence of tornadoes.

The Pacific - North American (PNA) pattern in boreal winter and spring is linked to the large-scale differential advection and the lower-level vertical wind shear in the central and eastern U.S. as discussed in earlier studies [e.g., Munoz and Enfield, 2011]. During a negative phase of the PNA, an anomalous cyclone is formed over North America that bring more cold and dry upper-level air from the high latitudes to the U.S., and an anomalous anticyclone is formed over the southeastern seaboard that increases the southwesterly wind from the GoM to the U.S., thus enhancing the Gulf-to-U.S. moisture transport. Additionally, the lower-level vertical wind shear is increased over the U.S. during a negative phase of the PNA due to the increased upper-level westerly and lower-level southeasterly. Although the PNA is a naturally occurring atmospheric phenomenon driven by intrinsic variability of the atmosphere, a La Niña in the tropical Pacific can project onto a negative phase PNA pattern [e.g., Straus and Shukla 2002]. In addition, since the Gulf-to-U.S. moisture transport can be enhanced with a warmer GoM, the sea surface temperature (SST) anomaly in the GoM can also affect U.S. tornado activity. During the decay phase of La Niña in spring, the GoM is typically warmer than usual. Therefore, the Gulf-to-U.S. moisture transport could be increased during the decay phase of La Niña in spring due to the increased SSTs in the GoM and the strengthening of the southwesterly wind from the GoM to the U.S. Nevertheless, none of these (i.e., PNA, GoM SST, and La Nina) are significantly correlated with the number of intense tornadoes in AM (see Table 1), consistent with earlier studies [e.g., Cook and Schaefer,  Currently, seasonal forecast skill for intense U.S. tornado outbreaks, such as occurred in 2011, has not been demonstrated.

Among the long-term climate patterns considered in Table 1, only the Trans-Niño (TNI) is significantly correlated ($r$ = 0.33) with the number of intense U.S. tornadoes in AM. The TNI, which is defined as the difference in normalized SST anomalies between the Niño-1+2 (10S° - 0°; 90°W - 80°W) and Niño-4 (5°N - 5°S; 160°E - 150°W) regions, represents the evolution of the El Niño-Southern Oscillation (ENSO) in the months leading up to the event and the subsequent evolution with opposite sign after the event [Trenberth and Stepaniak, 2001]. Given that AM is typically characterized with the development or decay phase of ENSO events, it is more likely that the tropical Pacific SST anomalies in AM are better represented by the TNI index than the conventional ENSO indices such as Niño-3.4 (5°N - 5°S; 170°W - 120°W) or Niño-3 (5°N - 5°S; 150°W-90°W). Nevertheless, it is not at all clear why the number of intense U.S. tornadoes in AM is significantly correlated with the TNI index, but not with other ENSO indices. This is the central question that we explore in the following sections by using both observations and an atmospheric general circulation model (AGCM).

## 2. Observations

To better understand the potential link between the TNI and U.S. tornado activity, we ranked the years from 1950 to 2010 (61 years in total) based on the number of intense (F3-F5) U.S. tornadoes in AM. The top ten years are characterized by an anomalous upper-level cyclone over North America that advects more cold and dry air to the U.S. (Figure 1a), increased Gulf-to-U.S. moisture transport (Figure 1b) and increased lower-level vertical wind shear over the central and eastern U.S. (Figure 1c), whereas the bottom ten years are associated with an anomalous upper-level anticyclone over North America (Figure 1d), decreased Gulf-to-U.S. moisture transport (Figure 1e) and decreased lower-level vertical wind shear over the central and eastern U.S. (Figure 1f).

Among the top ten years (Table S1), seven years including the top three are identified with a positive phase (i.e., within the upper quartile) TNI index (i.e., normalized SST anomalies are larger in the Niño-1+2 than in Niño-4 region). Five out of those seven years are characterized by a La Niña transitioning to a different phase or persisting beyond AM (1957, 1965, 1974, 1999, and 2008) and the other two with an El Niño transitioning to either a La Nina or neutral phase (1983 and 1998). Figure 2a shows the composite SST anomalies for those five positive phase TNI years transitioning from a La Niña.

On the other hand, among the bottom ten years (Table S2), only one year is identified with a positive phase TNI, and the other nine years are with a neutral phase TNI (i.e., between the lower and upper quartiles), suggesting that a negative phase of the TNI neither decreases nor increases the number of intense U.S. tornadoes in AM. Interestingly, four years among the bottom ten years are identified with a La Niña transitioning to a different phase or persisting beyond AM (1950, 1951, 1955 and 2001), and four are identified with an El Niño transitioning to a different phase or persisting beyond AM (1958, 1987, 1988 and 1992). As shown in Figure 2b, the composite SST anomaly pattern for the four years of the bottom ten years with a La Niña transitioning is that of a typical La Niña with the SST anomalies in the Niño-4 and Niño-1+2 being both strongly negative (i.e., neutral phase TNI). Similarly, as shown in Figure 2c, the composite SST anomaly pattern for the four years in the bottom ten years with an El Niño transitioning is that of a typical El Niño with the SST anomalies in the Niño-4 and Niño-1+2 being both strongly positive (i.e., neutral phase TNI).

In summary, observations indicate that a positive phase TNI (i.e., normalized SST anomalies are larger in the Niño-1+2 than in Niño-4 region) is linked to an increased number of intense U.S. tornadoes in AM, whereas both La Niñas and El Niños with a neutral phase TNI (i.e., the SST anomalies in the Niño-1+2 region are as strong and the same sign as the SST anomalies in the Niño-4) are linked to a decreased number of intense U.S. tornadoes in AM.

## 3. Model Experiments

To explore the potential link between the three tropical Pacific SST anomaly patterns (see Figure 2), identified in the previous section, and the number of intense U.S. tornadoes in AM, a series of AGCM experiments are performed by using version 3.1 of the NCAR community atmospheric model coupled to a slab mixed layer ocean model (CAM3). The model is a global spectral model with a triangular spectral truncation of the spherical harmonics at zonal wave number 42 (T42). It is vertically divided into 26 hybrid sigma-pressure layers. Model experiments are performed by prescribing various composite evolutions of SSTs in the tropical Pacific region (15°S–15°N; 120°E-coast of the Americas) while predicting the SSTs outside the tropical Pacific using the slab ocean model. To prevent discontinuity of SST around the edges of the forcing region, the model SSTs of three grid points centered at the boundary are determined by combining the simulated and prescribed SSTs. Each ensemble consists of ten model integrations that are initialized with slightly different conditions to represent intrinsic atmospheric variability. The same methodology was previously used in Lee et al. [2008] for studying ENSO teleconnection to the tropical North Atlantic region.

Four sets of ensemble runs are performed (Table S3). In the first experiment (EXP_CLM), the SSTs in the tropical Pacific region are prescribed with climatological SSTs. In the second experiment (EXP_TNI), the composite SSTs of the positive phase TNI years identified among the ten most active U.S. tornado years are prescribed in the tropical Pacific region. Note that only the five positive TNI years transitioning from a La Niña (1957, 1965, 1974, 1999, and 2008) are considered here because the other two positive TNI years are transitioning from an El Niño (1983 and 1998) and thus tend to cancel the tropical SST anomalies of the other five. In the next two experiments, the SSTs in the tropical Pacific region are prescribed with the composite SSTs of the four years in the bottom ten years with a La Niña transitioning (1950, 1951, 1955 and 2001) for EXP_LAN, and the four years in the bottom ten years with an El Niño transitioning (1958, 1987, 1988 and 1992) for EXP_ELN.

## 4. Model Results

In EXP_TNI (Figure 3), an anomalous upper-level cyclone is formed over North America that brings more cold and dry air to the U.S., and both the Gulf-to-U.S. moisture transport and the lower-level vertical wind shear over the central and eastern U.S. are increased, all of which are large-scale atmospheric conditions conducive to intense tornado outbreaks over the U.S. In EXP_ELN (Figure S2), on the other hand, the Gulf-to-U.S. moisture transport is neither increased nor decreased. The lower-level vertical wind shear is slightly decreased over the central and eastern U.S. mainly due to a weak anomalous upper-level anticyclone formed over North America. In EXP_LAN (Figure S2), a relatively weak anomalous upper-level cyclone is formed, and thus the lower-level vertical wind shear is slightly increased. However, the Gulf-to-U.S. moisture is not increased.

Therefore, these model results support the hypothesis that a positive phase of the TNI with cooling in the central tropical Pacific (CP) and warming in the eastern tropical Pacific (EP) enhances the large-scale differential advection in the central and eastern U.S. advecting more cold and dry upper-level air from the high latitudes and more warm and moist lower-level from the GoM, and increases the lower-level vertical wind shear therein, thus providing large-scale atmospheric conditions conducive to intense tornado outbreaks over the U.S. However, the model results do not show favorable large-scale atmospheric conditions in the central and eastern U.S. under La Niña and El Niño conditions as long as the SST anomalies in EP are as strong and the same sign as the SST anomalies in CP.

## 5. CP- versus EP-forced Teleconnection

The model results strongly suggest that cooling in CP and warming in EP may have a constructive influence on the teleconnection pattern that strengthens the large-scale differential advection and lower-level vertical wind shear over the central and eastern U.S. To better understand how the real atmosphere with moist diabatic processes responds to CP cooling and EP warming, two sets of additional model experiments (EXP_CPC and EXP_EPW) are performed (Table S3). These two experiments are basically identical to EXP_TNI except that the composite SSTs of the positive phase TNI years are prescribed only in the western and central tropical Pacific region (15°S–15°N; 120°E - 110°W) for EXP_CPC and only in the eastern tropical Pacific region (15°S–15°N; 110°W-coast of the Americas) for EXP_EPW.

In EXP_CPC (Figure 4), the teleconnection pattern emanating from the tropical Pacific consists of an anticyclone over the Aleutian Low in the North Pacific, a cyclone over North America, and an anticyclone over the southeastern U.S. extending to meso-Americas, consistent with a negative phase PNA-like pattern (Figure 4a). As expected from the anomalous anticyclonic circulation over the southeastern U.S. and meso-America, the Gulf-to-U.S. moisture transport is increased in EXP_CPC (Figure 4b). The lower-level vertical wind shear is increased over the central and eastern U.S. due to the strengthening of the upper-level westerly and lower-level southeasterly flow (Figure 4c).

Surprisingly, the Rossby wave train forced by warming in EP (EXP_EPW) is very similar to that in EXP_CPC (Figure 4d). Consistently, both the Gulf-to-U.S. moisture transport and the lower-level vertical wind shear over the central and eastern U.S. are also increased in EXP_EPW as in EXP_CPC and EXP_TNI (Figure 4e and f). A question arises as to why the teleconnection pattern forced by warming in EP is virtually the same as that forced by cooling in CP. It appears that the Rossby wave train in EXP_EPW is not directly forced from EP. In EXP_EPW, convection is increased locally in EP, but it is decreased in CP as in EXP_CPC (Figure S3c). This suggests that increased convection in EP associated with the increased local SSTs suppresses convection in CP that in turn forces a negative phase PNA-like pattern. Therefore, these model results confirm that cooling in CP and warming in EP do have constructive influence on the teleconnection pattern that strengthens the large-scale differential advection and lower-level vertical wind shear over the central and eastern U.S. The model results also suggest that cooling in CP with neutral SST anomalies in EP or warming in EP with neutral SST anomalies in CP can strengthen the large-scale differential advection and lower-level vertical wind shear over the central and eastern U.S.

An apparently important question is why warming in EP does not directly excite a Rossby wave train to the high-latitudes. As shown in earlier theoretical studies, the vertical background wind shear is one of the two critical factors required for tropical heating to radiate barotropic teleconnections to the high-latitudes [e.g., Lee et al. 2009]. In both observations and EXP_CLM, the background vertical wind shear between 200 and 850 hPa in AM is largest in the central tropical North Pacific and smallest in EP and the western tropical Pacific (WP), providing an explanation as to why the Rossby wave train in EXP_EPW is not directly forced in EP (Figure S4). See Lee et al. [2009] and references therein for more discussions on this issue.

**6. Effect of Internal Variability**

The record-breaking U.S. tornado outbreak in the spring of 2011 prompts the need to identify and understand long-term climate signals that could potentially provide seasonal predictability for intense tornado outbreaks. The conclusion so far is that a positive phase of the TNI, characterized by cooling in CP and warming in EP, may be one such climate pattern that can strengthen the large-scale differential advection and lower-level vertical wind shear in the central and eastern U.S., and thus providing favorable large-scale atmospheric conditions for a major tornado outbreak over the U.S. However, the TNI explains only 10% of the total variance in the number of intense U.S. tornadoes in AM. This suggests that intrinsic variability in the atmosphere may overwhelm the TNI-teleconnection pattern over North America as discussed in earlier studies for El Niño-teleconnection patterns in the Pacific–North American region [e.g., Hoerling and Kumar, 1997; Lee et al. 2008]. In other words, although seven of the ten most active tornado years during 1950-2010 including the top three years are characterized by a strongly positive phase of the TNI (Table S1), the associated predictability of U.S. tornado activity, which can be defined as a ratio of the climate signal (the TNI index in this case) relative to the climate noise, is low. Therefore, further study is needed to refine the predictive skill provided by the TNI and to explore other long-term climate signals that can provide additional predictability in seasonal and longer time scales.

## 7. U.S. Tornado Outbreaks in 2011

A positive phase of the TNI prevailed during AM of 2011 with cooling in CP and warming EP (Figure S5). An important question is whether the series of extreme U.S. tornado outbreaks during AM of 2011 can be attributed to this positive phase of the TNI. During AM of 2011, an anomalous upper-level cyclone was formed over the northern U.S. and southern Canada (Figure S6a), the Gulf-to-US moisture was greatly increased (Figure S6b), and the lower-level vertical wind shear was increased over the central U.S., all indicating the coherent teleconnection response to a positive phase of the TNI. To confirm this, a set of model experiments (EXP_011) is performed by prescribing the SSTs for 2010 - 2011 in the tropical Pacific region while predicting the SSTs outside the tropical Pacific using the slab ocean model (Table S3). As summarized in Figure S7, the model results are consistent with the observations, although the anomalous Gulf-to-US moisture transport is weaker in the model experiment.

A distinctive feature in the 2011 TNI event is warming in WP (Figure S5). Further experiments (Table S3) suggest that the warming in WP indirectly suppresses convection in CP, and thus works constructively with the cooling in CP to force a strong and persistent negative phase PNA-like pattern (Figure S8 and S9). Thus, despite the low signal-to-noise ratio in the

TNI-teleconnection response in the central and eastern U.S., it is highly likely that the 2011 positive phase TNI event did contribute to the U.S. tornado outbreak in AM of 2011 by enhancing the differential advection and lower-level vertical wind shear in the central and eastern U.S.

## 8. Discussion

It is important to discuss the limitations and caveats in this study, especially numerous known deficiencies in the SWD. For instance, Verbout et al. [2006] suggested that the decrease in the number of intense U.S. tornadoes in AM around the mid-1970s (see Figure S1b) is an artifact associated with changes in damage estimation procedures. Additionally, the structural damage-wind speed relationship and the associated tornado ratings cannot be completely objective or consistent over time because every particular tornado-structure interaction is different in detail and thus changes with time and case-to-case [Doswell et al., 2009]. Therefore, until such issues in the SWD are resolved, any tornado related climate research is subject to strong caveats.

A related issue is whether the number of intense tornadoes used in this study is the proper metric for representing tornado years. For instance, 60 out of the 85 intense (F3-F5) U.S. tornadoes in AM of 1974 occurred on one convective day. Thus, some years with a large number of tornadoes are not qualified as outbreak years if the single day with the largest number of tornadoes in each year is taken out. Due to this limitation in the tornado metric used in this study, it is important that we test our main conclusions using different tornado indices. Another widely used metric is the intense U.S. tornado-days, which is obtained by counting the number of days in which more than a threshold number of intense tornadoes occurred [e.g., Verbout et al. 2006].

The threshold number selected in this case is three and above, which roughly represents the upper 25% in the number of intense U.S. tornadoes in a given day of AM during 1950-2010. The time series of intense U.S. tornado-days in AM for 1950-2010 is shown in Figure S10. Table 1 is reproduced using this new metric. As shown in Table S4, the TNI is significantly correlated with the intense U.S. tornado-days in AM, supporting the overall conclusions of this study.

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**Table 1**. Correlation coefficients of various long-term climate patterns in December-February (DJF), February-April (FMA), and April and May (AM) with the number of intense (F3 - F5) tornadoes in AM during 1950-2010. All indices including the tornado index are detrended using a simple least squares linear regression. The SWD, ERSST3, and NCEP-NCAR reanalysis are used to obtain the long-term climate indices used in this table. Correlation coefficients above the 95% significance are in bold[a].

| Index | DJF | FMA | AM |
|---|---|---|---|
| Gulf-to-U.S. moisture transport | 0.08 | 0.20 | **0.40** |
| Lower-level vertical wind shear | 0.06 | 0.15 | **0.34** |
| GoM SST | 0.15 | 0.21 | 0.20 |
| Niño-4 | -0.22 | -0.20 | -0.19 |
| Niño-3.4 | -0.13 | -0.13 | -0.11 |
| Niño-1+2 | 0.02 | 0.11 | 0.15 |
| TNI | **0.28** | **0.29** | **0.33** |
| PNA | -0.05 | -0.10 | -0.20 |
| PDO | -0.12 | -0.10 | -0.14 |
| NAO | -0.01 | -0.10 | -0.18 |

[a]The Gulf-to-U.S. meridional moisture transport is obtained by averaging the vertically integrated moisture transport in the region of 25°N - 35°N and 100°W - 90°W. The lower-level (500 hPa – 925 hPa) vertical wind shear is averaged over the region of $30^{o}$N – $40^{o}$N and $100^{o}$W – $80^{o}$W. The North Atlantic Oscillation (NAO) index and the Pacific - North American (PNA)

pattern are defined as the first and second leading modes of Rotated Empirical Orthogonal Function (REOF) analysis of monthly mean geopotential height at 500 hPa, respectively. The Pacific Decadal Oscillation (PDO) is the leading principal component of monthly SST anomalies in the North Pacific Ocean north of 20°N.

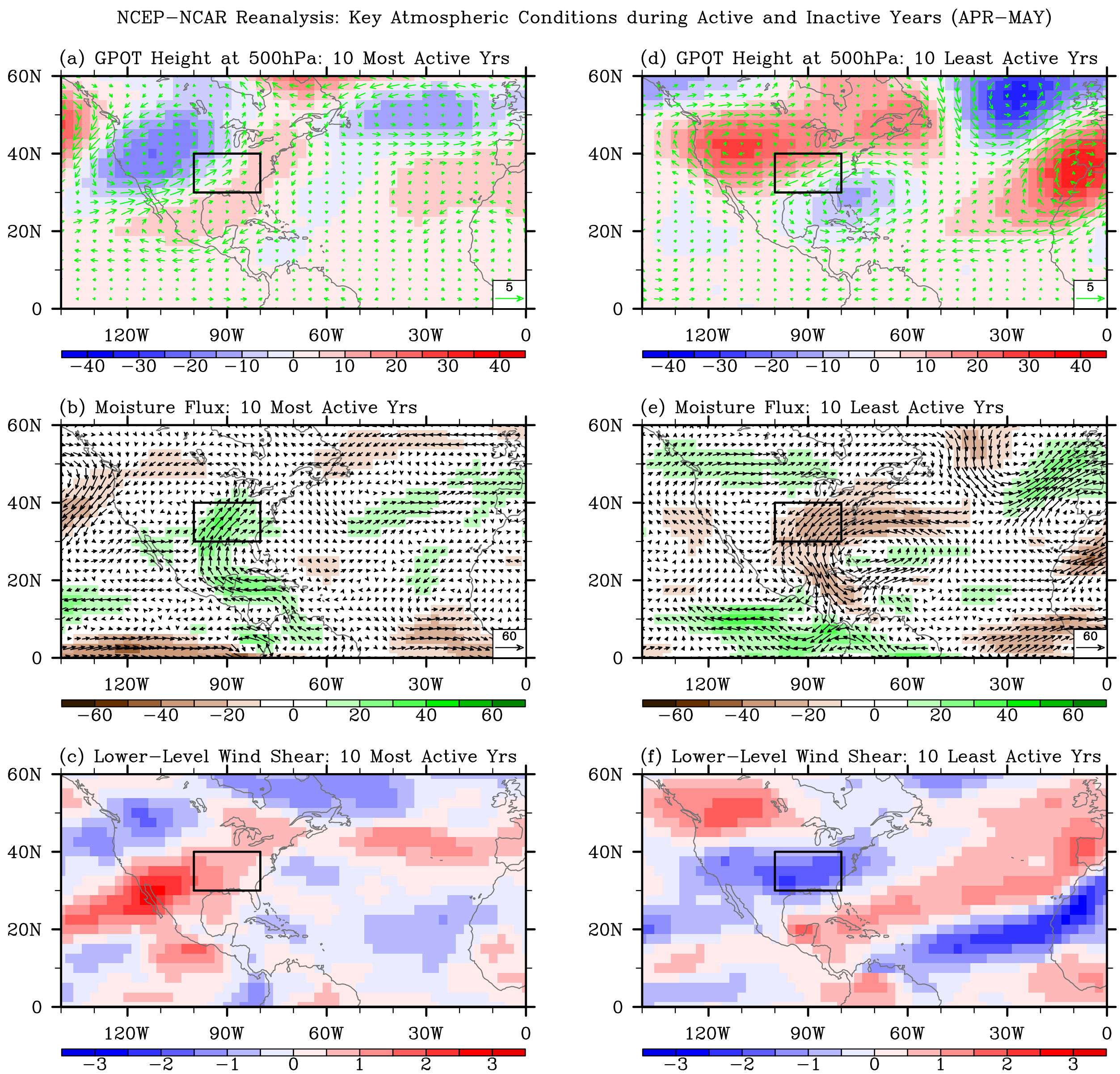


**Figure 1**. Anomalous geopotential height and wind at 500 hPa, moisture transport and lower-level (500 hPa – 925 hPa) vertical wind shear for the ten most active U.S. tornado years (a, b and c) and the ten least active U.S. tornado years (d, e and f) in AM during 1950-2010 obtained from NCEP-NCAR reanalysis. The units are kg $m^{-1}sec^{-1}$ for moisture transport, m for geopotential height, and m $s^{-1}$ for wind and wind shear. The small box in (a) - (f) indicates the central and eastern U.S. region frequently affected by intense tornadoes.

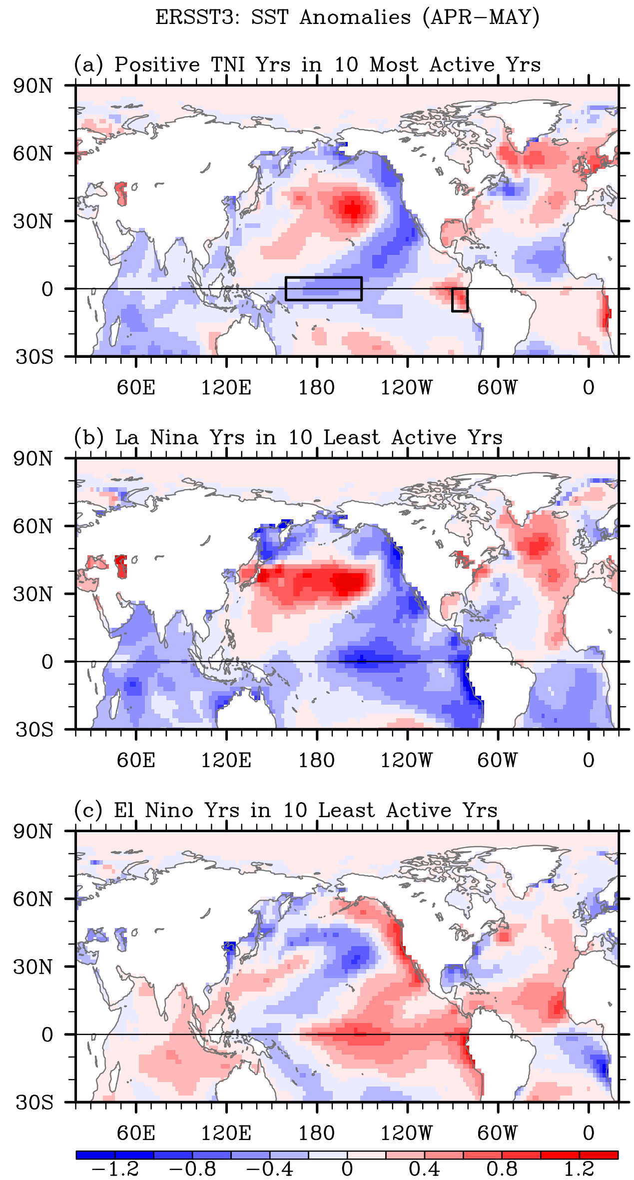


**Figure 2**. Composite SST anomalies in AM, obtained from ERSST3, for (a) the five positive TNI years transitioning from a La Niña identified among the ten most active U.S. tornado years in AM during 1950-2010, and for (b) the four years with a La Niña transitioning and (c) the four years with an El Niño transitioning identified among the ten least active U.S. tornado years in AM during 1950-2010. Thick black rectangles in (a) indicate the Niño-4 (5°N - 5°S; 160°E - 150°W) and Niño-1+2 (10S° - 0°; 90°W - 80°W) regions.

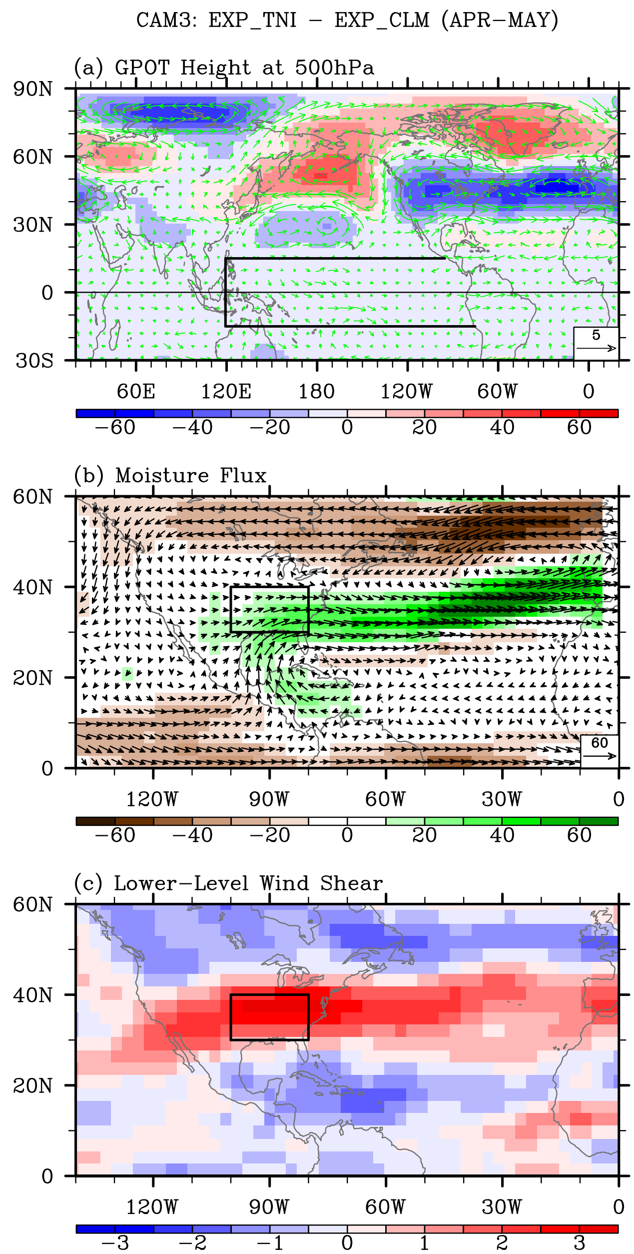


**Figure 3**. Simulated anomalous (a) geopotential height and wind at 500 hPa, (b) moisture transport and (c) lower-level (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_TNI – EXP_CLM. The units are kg $m^{-1}$ $sec^{-1}$ for moisture transport, m for geopotential height, and m $s^{-1}$ for wind and wind shear. Thick black lines in (a) indicate the tropical Pacific region where the model SSTs are prescribed. The small box in (b) and (c) indicates the central and eastern U.S. region frequently affected by intense tornadoes.

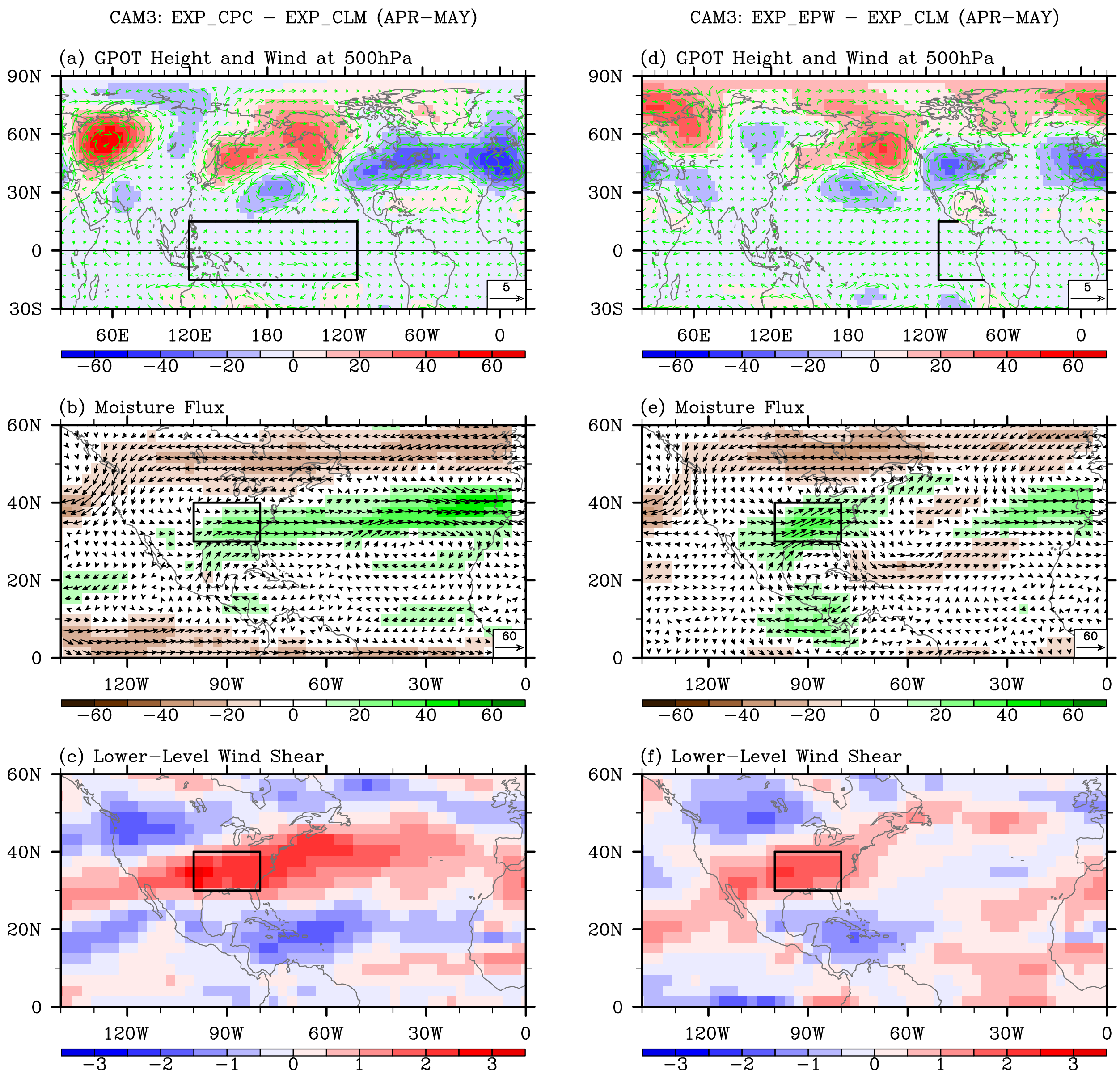


**Figure 4**. Simulated anomalous geopotential height and wind at 500 hPa, moisture transport, and lower-level (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_CPC – EXP_CLM (a, b and c), and EXP_EPW – EXP_CLM (d, e and f). The units are kg m$^{-1}$ sec$^{-1}$ for moisture transport, m for geopotential height, and m s$^{-1}$ for wind and wind shear. Thick black lines in (a) and (d) indicate the regions where the model SSTs are prescribed. The small box in (b), (c), (e) and (f) indicates the central and eastern U.S. region frequently affected by intense tornadoes.