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

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Corresponding Author:	Sang-Ki Lee, Ph.D. University of Miami Miami, FL UNITED STATES
Corresponding Author's Institution:	University of Miami
First Author:	Sang-Ki Lee, Ph.D.
Order of Authors:	Sang-Ki Lee, Ph.D.
	Robert Atlas, Ph.D.
	David Enfield, Ph.D.
	Chunzai Wang, Ph.D.
	Hailong Liu, Ph.D.
Abstract:	The record-breaking U.S. tornado outbreaks in the spring of 2011 prompt the need to identify long-term climate signals that could potentially provide seasonal predictability for intense U.S. tornado outbreaks. Here we use both observations and model experiments to show that a positive phase of Trans-Niño, characterized by colder than normal sea surface temperatures (SSTs) in the central tropical Pacific and warmer than normal SSTs in the eastern tropical Pacific, may be one such climate signal. Warmer-than-normal SSTs in the eastern tropical Pacific increase convection locally, but also contribute to suppressing convection in the central tropical Pacific. This in turn works constructively with colder than normal SSTs in the central tropical Pacific to force a strong and persistent 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-tropospheric 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 warmer than normal SSTs 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.
Suggested Reviewers:	Michael Alexander Michael.Alexander@noaa.gov
	Shang-Ping Xie xie@hawaii.edu
	Arun Kumar Arun.Kumar@noaa.gov
	Sang-Wook Yeh swyeh@hanyang.ac.kr
	Bohua Huang huangb@cola.iges.org

Corresponding author: Sang-Ki Lee
CIMAS, University of Miami and AOML, NOAA, Miami, FL 33149
E-mail) sang-ki.lee@noaa.gov

Dear Editor,

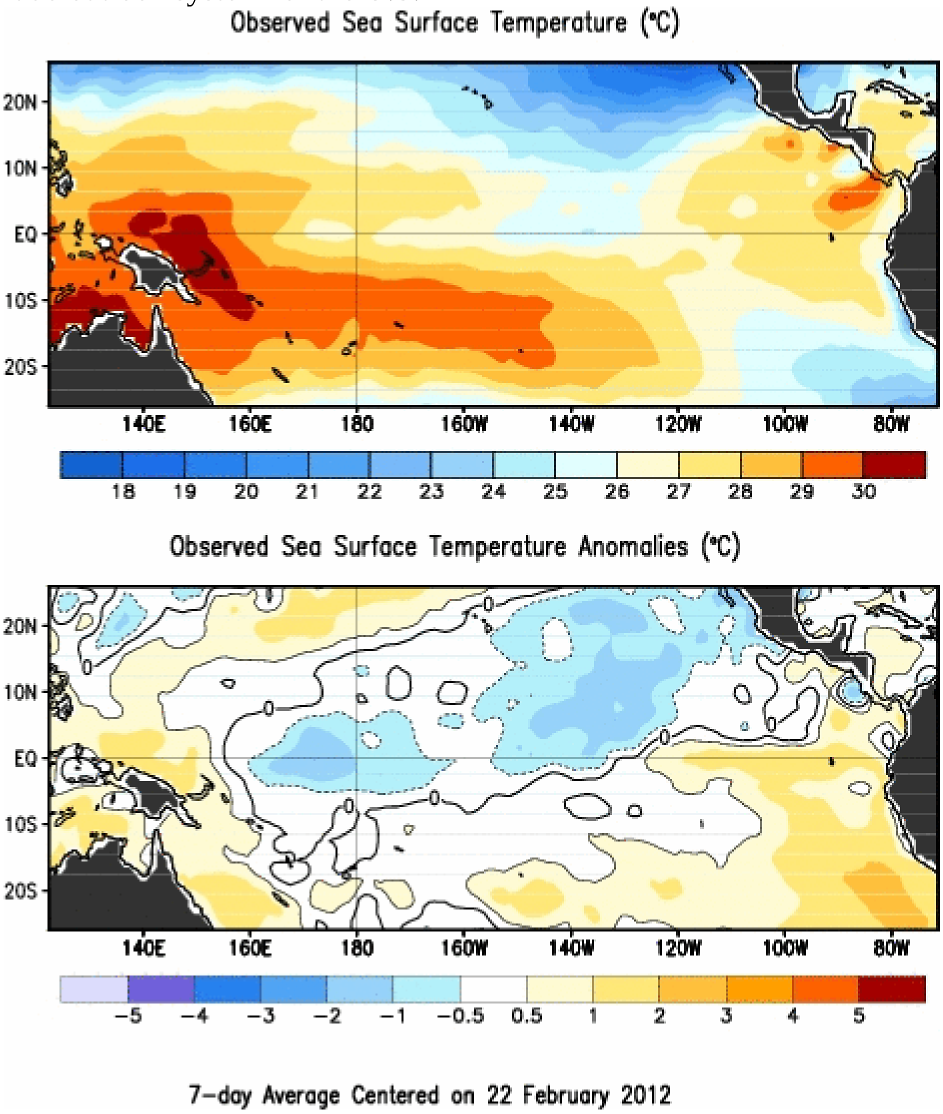
We wish to submit for your kind consideration for publication in Journal of Climate the enclosed manuscript entitled "Is there an optimal ENSO pattern that enhances large-scale atmospheric processes conducive to tornado outbreaks in the U.S?" by Sang-Ki Lee, Robert Atlas, David Enfield, Chunzai Wang, and Hailong Liu. Our original manuscript was previously submitted and rejected. However, since the comments from reviewer #1 and #3 were very encouraging, we have decided to submit a substantially revised version as a new manuscript. Our replies to the comments from the three reviewers are also attached.

The record-breaking U.S. tornado outbreak in the spring of 2011 prompts the scientific community to identify and understand long-term climate signals that may provide seasonal predictability for intense tornado outbreaks. Currently, seasonal forecast skill for intense U.S. tornado outbreaks, such as occurred in 2011, has not been demonstrated. Our study is the first one to suggest and show that a positive phase of the Trans-Niño (TNI), which is characterized by colder than normal SSTs in the central tropical Pacific and warmer than normal SSTs in the eastern tropical Pacific, provides favorable large-scale atmospheric conditions for major tornado outbreaks over the U.S.

In our manuscript, we use a correlation study in the introduction as a preliminary test to find a potential link between the TNI and tornado activity. We then used composite analysis of the top ten most extreme tornado outbreak years and the top ten positive TNI years to show that all of the critical environmental factors for U.S. tornado activity are favorable during those positive TNI years as in the top ten most extreme tornado outbreak years. We also found that among the top ten extreme tornado outbreak years, seven years including the top three are identified with a positive phase TNI. Then, we designed and performed extensive model experiments to confirm these findings and to understand the physical mechanisms.

It is troubling to find that reviewer #2 is very unfair and biased. First of all, he/she states throughout her/his comments as if our study relies heavily on correlation and significance. This is not a fair or correct summary of our work. We state in the beginning of section 3 that "the time series for the number of intense tornadoes is characterized by intense tornado outbreak years, such as 1974, 1965 and 1957, embedded amongst much weaker amplitude fluctuations". Naturally, we decided that an effective way to explore the tornado-climate relationship is to focus on the ten most extreme tornado years ranked from 1950 to 2010 instead of relying on correlation analysis. A related point is that we are mainly interested in the extreme U.S. tornado outbreak years and the associated large-scale environments because the majority of tornado-related fatalities occur during those extreme outbreak years. Perhaps, it is better that you read his/her review and our reply to each of his/her comment (attached) together to form your own opinion. If you find that his/her review on our previous manuscript is unfair and biased, we would like to request that he/she be removed from reviewing the revised manuscript and/or be replaced by a third reviewer. Although we do not believe that reviewer #2 can provide a fair and unbiased review, we understand that the final selection of reviewers is solely decided by the editor.

During the last week or so, a strong positive phase TNI has emerged in the tropical Pacific (picture attached). According to our study, this may lead to another destructive tornado season over the U.S. Frankly, we are quite anxious to publish our work so that we can move on to more extensive researches that may ultimately result in a development of seasonal tornado outlook system for the U.S.



Source of the image:
http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_update/sstweek_c.g

Finally, we would greatly appreciate a prompt and fair review of our revised manuscript.

Sincerely yours,

Sang-Ki Lee, Robert Atlas, David Enfield, Chunzai Wang, and Hailong Liu

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Decision Letter
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Ref.: JCLI-D-11-00691
Journal of Climate
Editor Decision

Dear Dr. Lee,

I am now in receipt of all reviews of the manuscript "Is there an optimal ENSO pattern that enhances large-scale atmospheric processes conducive to tornado outbreaks in the U.S?" by Sang-Ki Lee, Ph.D.; Robert Atlas, Ph.D.; David Enfield, Ph.D.; Hailong Liu, Ph.D.; Chunzai Wang, Ph.D..

Three reviewers have assessed your manuscript, and the reviews are mixed and often highly critical.

We would like to thank you and all three reviewers for their time and effort for reviewing our manuscript. Since the comments from reviewer #1 and #3 were very encouraging, we have decided to submit a substantially revised version as a new manuscript as you suggested. Our replies to the comments from the three reviewers are also attached.

Reviewer 2 feels that the statistical analysis (e.g. Pearson's correlation) and related significance tests employed here are flawed as they assume a Gaussian distribution.

It is troubling to find that reviewer #2 used such a strong language like “flawed” in his/her review of our work. We respectfully disagree with his/her unfair and biased characterization of our work. In the attached reply, we attempt to point out and explain that reviewer #2’s justifications for recommending rejection of our manuscript are very weak.

Regarding the issue of Pearson correlation (i.e., linear correlation), reviewer #2 points out that Pearson correlation is potentially problematic because the historical time series for the number of intense tornadoes (Figure 2a) is somewhat skewed. We understand this issue that limits the common practice of using linear correlation, although we also recognize that almost all meteorological/oceanographic data including ENSO are non-Gaussian in a strict sense. Therefore, we state in the beginning of section 3 that “the time series for the number of intense tornadoes is characterized by intense tornado outbreak years, such as 1974, 1965 and 1957, embedded amongst much weaker amplitude fluctuations”. Naturally, we decided that an effective way to explore the tornado-climate relationship is to focus on the ten most extreme tornado years ranked from 1950 to 2010, instead of relying on correlation analysis. We also would like to point out that, as our title suggests, we are mainly interested in the extreme U.S. tornado outbreak years and the associated large-scale environments because the majority of tornado-related fatalities occur during those extreme outbreak years. In other words, we are not really interested in small amplitude fluctuations in the number of tornadoes.

We found that among the top ten extreme years, seven of them including the top three are identified with a positive phase (within the upper quartile) TNI. Further analysis showed that the ten least active years are not linked to TNI because nine out of the ten least active years are under a neutral phase TNI. This also partially explains why the linear correlation between the number of intense tornadoes and TNI is not high.

Another important point, which reviewer #2 failed to recognize in his/her review, is that we also performed correlation analysis using the tornado-days index, which is a less skewed and widely used tornado index. As shown in Table 1 in parenthesis, this index is also significantly correlated with the TNI.

Reviewer #2 states throughout his/her review as if our study relies heavily on correlation and significance. For instance, reviewer #2 stated that we tested our hypothesis by computing the correlation of the various indices and made conclusions on the basis of significance. We believe that this is not a fair summary of our work. We used a correlation study in the introduction only as a preliminary test to find a potential link between the TNI and tornado activity. We then used composite analysis of the top ten most extreme tornado outbreak years and the top ten positive TNI years to show that all of the critical environmental factors for U.S. tornado activity are favorable during those positive TNI years (Figure 3 and 4) as in the top ten most extreme tornado outbreak years. We also found that among the top ten extreme tornado outbreak years, seven years including the top three are identified with a positive phase TNI. Then, we designed and performed extensive model experiments to confirm these findings and to understand the physical mechanisms.

Nevertheless, we agree with reviewer #2 that our significance test could be potentially problematic. Therefore, we decide to change "significantly correlated with" to "more strongly correlated with" in section 1 of the revised manuscript. Additionally, we remove our significance test in Table 1. We would like to point out that we did not use "significantly correlated" anywhere else in our original manuscript because we used a correlation study only in the introduction as a preliminary test.

Although the reviewer helpfully proposes some alternate statistical techniques that might be used, the reviewer doubts that these would produce statistically significant results.

Reviewer #2 applied ranking correlation methods (or nonparametric correlation methods) such as Kendall's tau and Spearman's rho to find that the TNI and the number of intense U.S. tornadoes in AM are not significantly correlated at 95% level. Ranking correlation methods (or nonparametric correlation methods) basically replace the number of tornadoes in a particular year to its ranking among the 61 years time series. Therefore, 1974 will be given the ranking of 1, and 1965 will be given the ranking of 2 and etc. Such methods almost always make the correlation computation robust in terms of statistical theory. We also understand that ranking correlations are widely used and have been shown to be useful in many scientific and engineering applications. However, a statistically robust method does not necessarily make it a scientifically sound and reasonable method for all cases. In fact, we do believe that ranking correlation methods (or nonparametric correlation methods) are not very effective analysis tools in our case because the extreme outbreak years such as 1974, 1965 and 1957 will have much less weight and thus the correlation will be largely determined by the embedded weak amplitude fluctuations. That is not what we are interested in our study. It is troubling to find that reviewer #2 failed to recognize this important point in our manuscript. As our title suggests, we are mainly interested in the extreme U.S. tornado outbreak years and the associated large-scale environments because the majority of tornado-related fatalities occur during those extreme outbreak years. Therefore, we used composite analysis of the top ten most extreme tornado outbreak years and the top ten positive TNI years to show that all of the critical environmental factors for U.S. tornado activity are favorable during those positive TNI years (Figure 3 and 4) as in the top ten most extreme tornado outbreak years. We also found that among the top ten extreme tornado outbreak years, seven years including the top three are identified with a positive phase TNI.

Reviewer #2 also performed Pearson correlation after removing 1974 to find that the correlation was not significant. We understand that this method was used in Munoz and Enfield (2011). After removing 1974, they also smoothed their tornado time series before performing linear correlation analysis. We respectfully disagree with reviewer #2 that this somewhat unorthodox method of removing 1974 then smoothing the tornado time series is an effective way to explore the relationship between the TNI and the number of intense tornadoes. Furthermore, the correlation between the TNI and the number of intense tornadoes is not very strong, although it is highest among the climate indices considered in Table 1, as correctly pointed out by reviewer #3. In fact, it is slightly above the 95% significance level. Therefore, removing any one year that contributes positively to the correlation will surely make the correlation below 95% significance. Therefore, this result from the reviewer is not surprising.

In summary, we believe that the two alternative methods (i.e., using ranking correlation and performing linear correlation after removing 1974) suggested by reviewer #2 are not suitable for our study. However, we agree with reviewer #2 that our significance test could be potentially problematic. Therefore, we changed “significantly correlated with” to “more strongly correlated with” in section 1 of the revised manuscript. Additionally, we remove our significance test in Table 1. We would like to point out that we did not use “significantly correlated” anywhere else in our original manuscript because we used a correlation study only in the introduction as a preliminary test.

Reference:

Munoz, E., and D.B. Enfield. The boreal spring variability of the Intra-Americas low-level jet and its relation with precipitation and tornadoes in the eastern United States. Climate Dynamics, 36(1-2):247-259, doi:10.1007/s00382-009-0688-3 2011

Reviewer 2 also feels that statistical significance for the relationships described in Section 3 need to be established.

In the revised manuscript, the values for 90% significance are stated in all the figure captions.

Further, the reviewer cites lack of basic analyses that would provide support for the results, such as a simple scatterplot of the Nino index and intense tornadoes.

We respectfully disagree with reviewer #2 on this point. We did show in Figure 4 that the top ten positive TNI years during 1950-2010 are associated with (1) an anomalous upper-level cyclone over North America that advects more cold and dry air to the U.S. (Figure 4a), (2) increased Gulf-to-U.S. moisture transport (Figure 4b), and (3) increased lower-tropospheric vertical wind shear over the U.S (Figure 4c) as we discussed in section 3. All of these large-scale atmospheric circulations are conducive to intense tornado outbreaks over the U.S., and consistent with those during the ten most extreme tornado years as shown in Figure 3a, b and c. We also believe that Table1, 2, 3, Figure 3, 4, 5, 6 and the associated discussions in section3 are basic analyses that link a positive phase TNI with increased tornado activity over the U.S.

Furthermore, as we discussed above, we are not interested in the overall correlation between the TNI and the number of intense tornadoes in AM because we did find that the correlation is not strong as shown in Table 1. An addition of a scatter plot will simply reiterate this point. Instead, we are interested in the extreme outbreak years, which are extensively analyzed in our study. Therefore, we do not think that showing a scatter plot is necessary or useful. Additionally, we now have 19 figures and 4 tables. We would like to find a way to remove some of them not to add more.

Reviewer 3 expresses general disappointment and lack of surprise at the weak correlations between ENSO and intense tornadoes, as tornadogenesis is fundamentally a mesoscale problem that makes diagnosing the right mix of conditions in long-term averages problematic.

This issue of long-term averaged climate processes versus short-term weather processes has long been debated in hurricane research community. We understand that, as in tornadogenesis, hurricane genesis requires overlap of a very specific combination of ocean and atmospheric conditions. However, it is now widely recognized that, in a long-term averaged sense, an El Nino condition in the tropical Pacific tends to suppress the genesis and development of Atlantic hurricanes through its remote influence that increases the vertical wind shear over the tropical Atlantic Ocean.

Therefore, we fully understand and agree with reviewer #3's point that tornadogenesis is basically a mesoscale problem, and that it requires overlap of very specific local atmospheric conditions. We also agree that tornadogenesis is not expected to be adequately captured by large-scale and long-term averaged atmospheric processes. In this study, we simply argue that such overlap of the specific conditions for tornadogenesis may occur more frequently on average during a positive phase of the TNI than during a neutral phase of the TNI. These points are now discussed in section3 and section 9 of the revised manuscript.

Further, both Reviewers 2 and 3 cite a lack of direct diagnosis of the relationship between the TNI index and quantities such as low-level shear and lower LCL that are cited as important for tornado activity.

In the revised manuscript, we add a new plot (Figure 19) for low-level shear between 850mb and 1000mb, which roughly represents the 0-1 km shear. As shown in this figure, low-level vertical wind shear in AM is increased over the central and eastern U.S during both the ten most active tornado years and top ten positive TNI years. This is also well simulated in EXP_TNI – EXP_CLM (Figure 19c). Other important factors such as lifting condensation level height and convective inhibition and their associations with TNI will be explored in a future study. These points are now added in section 9 of the revised manuscript.

While Reviewer 1 was generally positive about the manuscript, the reviewer still has fundamental questions about the physics of the ENSO teleconnection in the context of the index used and importance of SST in different regions of the Pacific for establishing the relevant teleconnection to tornado activity.

We understand that reviewer #1's core question (or concern) are "*If so, why is SST´(Nino 1+2) needed in this index of TNI? What is the exact role of SST´(Nino 1+2) in forging the large-scale conditions favoring severe tornadoes?*". We believe that we already addressed this issue in our original manuscript (this point is summarized below). On this point, reviewer #2 also states that *"….and it was also suggested that the warmer SST(Nino 1+2) was not the source exciting the Rossby waves and attributed little to the anomaly patterns favoring tornadoes."*. This statement is a misunderstanding. We did find that warmer than normal SSTs in the eastern tropical Pacific (EP) contribute to the large-scale atmospheric patterns favoring tornado activity in the U.S. The stationary Rossby waves are excited in response to the warm EP. But, they are not directly forced by the warm EP, but rather indirectly by the reduced convection in CP. In summary, warmer than normal SSTs in EP suppress deep convection in CP and thus do force stationary Rossby waves over the North America in favor of increased U.S. tornado activity.

A core question is how increased convection in EP associated with the increased local SSTs suppresses convection in CP remotely. Although finding the answer to this question requires a separate and more extensive study, one plausible explanation is that the warmer than normal SSTs in EP induces a global average warming of the tropical troposphere via a fast tropical teleconnection mechanism (e.g., Chiang and Sobel 2002), and thus increases atmospheric static stability and decreases convection over CP and other tropical regions of normal SSTs. A similar argument was previously used in Lee et al. (2011) to explain reduced deep convection in the tropical Atlantic in response to warmer than normal SSTs in the tropical Pacific. Another similar argument, but in a different context, is the "upped-ante mechanism", which is often used to explain anomalous descent motions neighboring warm SST anomalies in the eastern and central Pacific Ocean during El Niño (Su and Neelin 2002; Neelin et al. 2003). We now discuss these points in section 6 of the revised manuscript.

A substantial amount of work will be required to address the reviewers' comments. Hence, based on the reviewers' recommendations and my own evaluation, I am sorry to inform you that this manuscript is rejected for publication in the Journal of Climate

We believe that our manuscript is now substantially revised and addresses all of the major comments from the three reviewers. However, it is troubling to find that reviewer #2 is very unfair and biased. Perhaps, it is better that you read his/her review and our reply to each of his/her comment (attached) together to form your own opinion. If you agree that his/her review on our previous manuscript is unfair and biased, we would like to request that he/she be removed from reviewing the revised manuscript and/or be replaced by a third reviewer. Although we do not believe that reviewer #2 can provide a fair and unbiased review, we understand that the final selection of reviewers is solely decided by the editor.

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Reviewer #1:

Review of "Is there an optimal ENSO pattern that enhances large-scale atmospheric processes conducive to tornado outbreaks in the U.S?" by Lee at el.

This is an interesting study of large-scale circulation conditions conducive to strong and frequent tornado events in the southeastern U.S. during April and May. The methods were sound, the manuscript was well written, and the results are useful for further understanding tornadic conditions and for improving skills of predicting strong tornadoes in the U.S. I thus recommend acceptance of this manuscript for publication in the Journal of Climate after the authors have addressed these following questions and issues in their revision.

We would like to thank all three reviewers for their time and effort for reviewing our manuscript. Since the comments from reviewer #1 and #3 were very encouraging, we have decided to submit a revised version as a new manuscript. First of all, we would like to thank the reviewer #1 for the encouragement and the thoughtful comments. The manuscript is now revised substantially based on these comments.

1. Lines 4-6 on page 4, "The TNI, which is defined as the difference in normalized SST anomalies between the Niño-1+2 (10S°-0°; 90°W-6 80°W) and Niño-4 (5°N-5°S; 160°E-150°W) regions, …" In other words, TNI=SST´(Nino 1+2) - SST´(Nino 4). Because a strong positive TNI is a desirable condition for severe tornadoes, bigger negative values of the SST´(Nino 4), or colder SST in the central equatorial Pacific, would favor severe tornado development. This raises several questions: a) Would it be true that the bigger the negative anomalies in SST´(Nino 4) the stronger the favorable circulation anomalies for tornadoes? b) If so, why is SST´(Nino 1+2) needed in this index of TNI? What is the exact role of SST´(Nino 1+2) in forging the large-scale conditions favoring severe tornadoes? These questions also emerged later in section 6 where it was shown that the colder SST(Nino 4) resulted in large-scale circulation anomaly patterns similar to those in years with most active severe tornadoes (Figs. 3a-c) and it was also suggested that the warmer SST(Nino 1+2) was not the source exciting the Rossby waves and attributed little to the anomaly patterns favoring tornadoes.

There is apparently additional work required to examine and clarify the role of the warmer SST (Nino 1+2) in the large-scale circulation anomalies favoring the severe tornadoes. Such work could be for a separate study, and for now a revision for more consistent discussions in the later sections in the manuscript on the role of the SST(Nino 1+2) (which was quite downplayed) with those in the earlier sections would balance this story better.

Regarding "*(a) Would it be true that the bigger the negative anomalies in SST´(Nino 4) the stronger the favorable circulation anomalies for tornadoes?*", further model experiments with both reduced and increased cold SST anomalies in the central tropical Pacific (CP) are required to answer this question. We have already performed ten sets of model experiments to address the core questions regarding the relationship between the TNI and tornadic environments (two more experiments are added in the revised manuscript). Therefore, we have too many results and figures (total 18 figures) to show them all in this paper. We feel that this question raised by reviewer #2 can be addressed in a follow-up paper.

Regarding "*(b) If so, why is SST´(Nino 1+2) needed in this index of TNI? What is the exact role of SST´(Nino 1+2) in forging the large-scale conditions favoring severe tornadoes?*", we believe that we already addressed this issue in our original manuscript. On this point, reviewer #2 also states that *"….and it was also suggested that the warmer SST(Nino 1+2) was not the source exciting the Rossby waves and attributed little to the anomaly patterns favoring tornadoes."*. This statement is a misunderstanding. We did find that warmer than normal SSTs in the eastern tropical Pacific (EP) contribute to the large-scale atmospheric patterns favoring tornado activity in the U.S. The stationary Rossby waves are excited in response to the warm EP. But, they are not directly forced by the warm EP, but rather indirectly by the reduced convection in CP. In summary, warmer than normal SSTs in EP suppress deep convection in CP and thus force stationary Rossby waves over the North America in favor of increased U.S. tornado activity. A core question is how increased convection in EP associated with the increased local SSTs suppresses convection in CP remotely. Although finding the answer to this question requires a separate and more dedicated study, one plausible explanation is that the warmer than normal SSTs in EP induces a global average warming of the tropical troposphere via a fast tropical teleconnection mechanism (e.g., Chiang and Sobel 2002), and thus increases atmospheric static stability and decreases convection over CP and other tropical regions of normal SSTs. A similar argument was previously used in Lee et al. (2011) to explain reduced deep convection in the tropical Atlantic in response to warmer than normal SSTs in the tropical Pacific. Another similar argument, but in a different context, is the "upped-ante mechanism", which is often used to explain anomalous descent motions neighboring warm SST anomalies in the eastern and central Pacific Ocean during El Niño (Su and Neelin 2002; Neelin et al. 2003). We now discuss these points in section 6 of the revised manuscript.

2. If the SST´(Nino 1+2) was not the source for the Rossby waves and the associated anomaly patterns shown in Figs. 8d-f, what could be the source for such anomalies? This question should be addressed or their discussion of the results in Fig. 8 would be incomplete.

As we discuss above, we believe that this question regarding the mechanism by which warmer than normal SSTs EP affect the stationary Rossby waves is addressed in section 6 of the revised manuscript. As reviewer #2 points out here, warmer than normal SSTs in EP and the associated increase in local convection activity do not directly excite the stationary Rossby waves because the background vertical wind shear, one of the two critical background states for teleconnection, is very weak in the eastern Pacific during AM (Figure 13). Our analysis of EXP_EPW suggests that warmer than normal SSTs in EP tends to decrease deep convection activity in CP (Figure 12c). Therefore, the reduced convection in CP, in turn, produces a robust teleconnection over the North America to increase U.S tornado activity. In section 6 of the revised manuscript, we also add discussions to address how increased convection in EP associated with the increased local SSTs suppresses convection in CP remotely.

3. In producing the results shown in Figs. 8d-f what were the calculated SST anomalies in the central equatorial Pacific in the EXP_EPW experiment? (As described in the manuscript, the SST outside the eastern equatorial Pacific in this case was calculated by a slab ocean model.) Was the calculated SST in CP colder than the climatology? Also, what were the calculated SST anomalies in the EP in the EXP_CPC experiment? Was the SST in the EP warmer than the climatology? If such anomalies in the SST were shown in the calculations a different process *may have governed the phenomenon described by the TNI and affecting the tornado environment.*

In EXP_EPW, the eastern Pacific SSTs are prescribed using the five positive TNI years identified in Table 2. The SSTs in the rest of the tropical Pacific are fixed to climatology. The slab ocean model is used only outside the tropical Pacific region. Thus, SSTs in the central Pacific are simply those of climatology in EXP_EPW. We revised section 4 and Table 4 to clarify this point.

Reviewer #2

I have reviewed this manuscript in an earlier form. I have mostly the same comments.

We would like to thank all three reviewers for their time and effort for reviewing our manuscript. Since the comments from reviewer #1 and #3 were very encouraging, we have decided to submit a revised version as a new manuscript. First of all, we sincerely appreciate reviewer #2 for a careful review. We also would like to thank her/him for the earlier comments on our previous submission to a different journal.

The hypothesis is that SST associated with positive values of the Trans-Nino index (TNI) causes enhanced vertical shear and moisture transport in the US during April-May, and this in turn is related to tornado outbreaks.

This hypothesis is first tested by computing the correlation of the various indices and making conclusions on the basis of significance.

Reviewer #2 state here that we tested our hypothesis by computing the correlation of the various indices and made conclusions on the basis of significance. We believe that this is not a fair summary of our work. We used a correlation study in the introduction only as a preliminary test to find a potential link between the TNI and tornado activity. We then used composite analysis of the top ten most extreme tornado outbreak years and the top ten positive TNI years to show that all of the critical environmental factors for U.S. tornado activity are favorable during those positive TNI years (Figure 3 and 4) as in the top ten most extreme tornado outbreak years. We also found that among the top ten extreme tornado outbreak years, seven years including the top three are identified with a positive phase TNI. Then, we designed and performed extensive model experiments to confirm these findings and to understand the physical mechanisms.

In particular, TNI is found to be significantly correlated with the number of AM "intense" (F3 or greater) tornadoes. A major problem is that the use of Pearson's correlation is not suitable for tornado count data, especially intense tornadoes. Pearson's correlation, and, more importantly, the associated null hypothesis used for significance testing assume Gaussian distributions. Tornado count data is not expected to be Gaussian, and this data does not look it. There is no mention of this important issue in this manuscript, despite the heavy reliance on "significance". Pearson's correlation is strongly effected by outliers.

Regarding the issue of Pearson correlation (i.e., linear correlation), reviewer #2 points out that Pearson correlation is potentially problematic because the historical time series for the number of intense tornadoes (Figure 2a) is somewhat skewed. We understand this issue that limits the common practice of using linear correlation, although we also recognize that almost all meteorological/oceanographic data including ENSO are non-Gaussian in a strict sense. Therefore, we state in the beginning of section 3 that “the time series for the number of intense tornadoes is characterized by intense tornado outbreak years, such as 1974, 1965 and 1957, embedded amongst much weaker amplitude fluctuations”. Naturally, we decided that a more effective way to explore the tornado-climate relationship is to focus on the ten most extreme tornado years ranked from 1950 to 2010. We also would like to remind reviewer #2 that, as our title suggests, we are mainly interested in the extreme U.S. tornado outbreak years and the associated large-scale environments because the majority of tornado-related fatalities occur during those extreme outbreak years. In other words, we are not really interested in small amplitude fluctuations in the number of tornadoes.

We found that among the top ten extreme years, seven of them including the top three are identified with a positive phase (within the upper quartile) TNI. Further analysis showed that the ten least active years are not linked to TNI because nine out of the ten least active years are under a neutral phase TNI. This also partially explains why the linear correlation between the number of intense tornadoes and TNI is not high.

Another important point is that we also performed correlation analysis using the tornado-days index, which is less a skewed and widely used tornado index. As shown in Table 1 in parenthesis, this index is also significantly correlated with the TNI.

In summary, reviewer #2 states here as if our study relies heavily on correlation and significance. We believe that this is misunderstanding. We also believe that this is not a fair judgment of our work. However, we agree with reviewer #2 that our significance test could be potentially problematic. Therefore, we decide to change "significantly correlated with" to "more strongly correlated with" in section 1 of the revised manuscript. Additionally, we remove our significance test in Table 1. We would like to point out that we did not use "significantly correlated" anywhere else in our original manuscript.

Nonparametric measures such as Kendall's tau and Spearman's rho are unaffected by outliers. I computed Kendall's tau and Spearman's rho to measure the relation between the TNI and intense AM tornadoes and found neither was significant. When 1974 (an outlier in number of intense tornadoes) was removed from the analysis, the Pearson correlation was no longer significant at the 95% level.

Reviewer #2 applied ranking correlation methods (or nonparametric correlation methods) such as Kendall's tau and Spearman's rho to find that the TNI and the number of intense U.S. tornadoes in AM are not significantly correlated at 95% level. Ranking correlation methods (or nonparametric correlation methods) basically replace the number of tornadoes in a particular year to its ranking among the 61 years time series. Therefore, 1974 will be given the ranking of 1, and 1965 will be given the ranking of 2 and etc. Such methods almost always make the correlation computation robust in terms of statistical theory. We also understand that ranking correlations are widely used and have been shown to be useful in many science/engineering applications. However, a statistically robust method does not necessarily make it a scientifically sound and reasonable method for all cases. In fact, we do believe that ranking correlation methods (or nonparametric correlation methods) are not very effective analysis tools in our case because the extreme outbreak years such as 1974, 1965 and 1957 will have much less weight and thus the correlation will be largely determined by the embedded weak amplitude fluctuations. That is not what we are interested in our study. As our title suggests, we are mainly interested in the extreme U.S. tornado outbreak years and the associated large-scale environments because the majority of tornado-related fatalities occur during those extreme outbreak years. Therefore, we used composite analysis of the top ten most extreme tornado outbreak years and the top ten positive TNI years to show that all of the critical environmental factors for U.S. tornado activity are favorable during those positive TNI years (Figure 3 and 4) as in the top ten most extreme tornado outbreak years. We also found that among the top ten extreme tornado outbreak years, seven years including the top three are identified with a positive phase TNI.

Reviewer #2 also performed Pearson correlation after removing 1974 to find that the correlation was not significant. We understand that this method was used in Munoz and Enfield (2011). After removing 1974, they also smoothed their tornado time series before performing linear correlation analysis. We respectfully disagree with reviewer #2 that this somewhat unorthodox method of removing 1974 then smoothing the tornado time series is an effective way to explore the relationship between the TNI and the number of intense tornadoes. Furthermore, the correlation between the TNI and the number of intense tornadoes is not very strong, although it is highest among the climate indices considered in Table 1, as correctly pointed out by reviewer #3. In fact, it is slightly above the 95% significance level. Therefore, removing any year that contributes positively to the correlation will likely make the correlation under 95% significance. Therefore, this result from the reviewer is not surprising.

In summary, we believe that the two alternative methods (i.e., using ranking correlation and performing linear correlation after removing 1974) suggested by reviewer #2 are not suitable for our study. However, we agree with reviewer #2 that our significance test could be potentially problematic. Therefore, we changed “significantly correlated with” to “more strongly correlated with” in section 1 of the revised manuscript. Additionally, we remove our significance test in Table 1. We would like to point out that we did not use “significantly correlated” anywhere else in our original manuscript.

Reference:

Munoz, E., and D.B. Enfield. The boreal spring variability of the Intra-Americas low-level jet and its relation with precipitation and tornadoes in the eastern United States. Climate Dynamics, 36(1-2):247-259, doi:10.1007/s00382-009-0688-3 2011

Other issues are the use of “intense” rather than the more common "significant" (F2 and greater), and the fact that the tornado data is inhomogeneous with well-known factors causing shifts and trends in the time series.

Tornado-related climate studies so far have mainly used F1-F5 after Verbout et al. (2006). This study showed that F2-F5, suggested by reviewer #2, is not stationary for the period of 1954-2003. One study that we are aware of using F2-F5 is Munoz and Enfield (2011). Munoz and Enfield (2011) in page 225 lines 4-5 states “The tornadoes counted were category F2 and stronger (i.e., significant tornadoes) on the F-scale for tornado intensity” without providing any justification or reference for using it. Therefore, we are not aware of any scientific reason why using F3-F5 instead of using F2-F5 is a problem. Furthermore, as we stated in our original manuscript, 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. Therefore, the chance (or probability) that a F2-scale tornado is unreported is much higher than the chance that a F3-scale tornado is unreported before the 1990s. Therefore, we have a good reason to believe that the historical time series of F3-F5 are less likely to be affected by, although not completely free form, many known issues in the historical tornado data base compared to the F2-F5 data. Note that the occurrence of F4-F5 tornadoes is too rare to use it as a reliable index.

A scatter plot of TMI and AM tornadoes should be shown.

We respectfully disagree with reviewer #2 on this point. As we discussed earlier in our reply, we are not interested in the overall correlation between the TNI and the number of intense tornadoes in AM because we did find that the correlation is not strong as shown in Table 1. An addition of a scatter plot will simply reiterate this point. Instead, we are interested in the extreme outbreak years, which are extensively analyzed in our study. Therefore, we do not think that showing a scatter plot is necessary or useful. Additionally, we now have 19 figures and 4 tables. We would like to find a way to remove some of them not to add more.

The statistical significance should be computed for the results of section 3.

Statistical significance test is performed. The values for 90% significance are stated in the figure captions. In Table 2 and 3, strongly positive (i.e. the upper quartile) and negative (i..e, the lower quartile) TNI years are in bold and italic respectively.

Some statistical significance should be attached to the composite maps.

Statistical significance test is performed. The values for 90% significance are stated in the figure captions.

The selection of the SSTs that go into model runs EXP_TNI seems odd. It is neither a objective selection of the top 10 tornado years nor the top 10 TNI years. This makes it hard to interpret.

In the revised manuscript, two additional experiments similar to EXP_TNI are carried out by prescribing the SSTs in the tropical Pacific region with the composite SSTs of the top ten positive TNI years for EXP_TN1, and the top ten most extreme tornado years for EXP_TN2. All of the large-scale atmospheric conditions conducive to intense tornado outbreaks over the U.S. are well reproduced in both EXP_TN1 and EXP_TN2 as shown in Figure 9.

The correlation of TNI with the vertical shear and moisture transport indices should computed. If TNI is to be linked to tornadoes via shear and moisture, then this intermediate connection should be checked.

We respectfully disagree with reviewer #2 on this point. We did show in Figure 4 that the top ten positive TNI years during 1950-2010 are associated with (1) an anomalous upper-level cyclone over North America that advects more cold and dry air to the U.S. (Figure 4a), (2) increased Gulf-to-U.S. moisture transport (Figure 4b), and (3) increased lower-tropospheric vertical wind shear over the U.S (Figure 4c) as we discussed in section 3. All of these large-scale atmospheric circulations are conducive to intense tornado outbreaks over the U.S., and consistent with those during the ten most extreme tornado years as shown in Figure 3a, b and c. We also believe that Table1, 2, 3, Figure 3, 4, 5, 6 and the associated discussions in section3 are basic analyses that link a positive phase TNI with increased tornado activity over the U.S.

Why is optimal in the title? What does it mean? There is no discussion of optimality in the text.

Tropical SST patterns associated with ENSO are different year-by-year. Trenberth and Stepaniak [2001] used a terminology "different flavor of ENSO" to stress this point. The main objective of this paper is to find one such flavor of ENSO that enhances large-scale environment conducive to tornado outbreaks in U.S. Therefore, we think that the current title is appropriate for our manuscript. We add the following sentence in section 7 of the revised manuscript: "In this sense, a positive phase of the TNI may be an optimal ENSO pattern that increases the chance for major U.S. tornado outbreaks.".

In summary, I think that there seems to be a connection between TNI and moisture/shear, which could be made more precise. I'm not sure if the ranking of years by TNI and AM tornadoes (section 3) shows a statistically significant relation. This can be checked. I don't think that the interpretation of the correlation of indices (Table 1) is correct.

We believe that we made it very precise that a positive phase of TNI is associated with favorable environmental conditions for extreme tornadoes outbreak in the U.S. by using various composite analysis and extensive model experiments.

Regarding the reviewer's comment "*I'm not sure if the ranking of years by TNI and AM tornadoes (section 3) shows a statistically significant relation*", as we point out earlier, we do not think that ranking correlation methods (or nonparametric correlation methods) are suitable for our study because the extreme outbreak years such as 1974, 1965 and 1957 will have much less weight and thus the correlation will be largely determined by the embedded weak amplitude fluctuations. We are not interested in the relationship between the TNI and the weak amplitude fluctuations of the tornado activity. As our title suggests, we are interested in the extreme U.S. tornado outbreak years and the associated large-scale environments because the majority of tornado-related fatalities occur during those extreme outbreak years.

Although we believe that the two alternative methods (i.e., using ranking correlation and performing linear correlation after removing 1974) suggested by reviewer #2 are not suitable for our study, we agree with reviewer #2 that our significance test could be potentially problematic. Therefore, we changed "significantly correlated with" to "more strongly correlated with" in section 1 of the revised manuscript. Additionally, we remove our significance test in Table 1.

Reviewer #3

We would like to thank all three reviewers for their time and effort for reviewing our manuscript. Since the comments from reviewer #1 and #3 were very encouraging, we have decided to submit a revised version as a new manuscript. First of all, we would like to thank reviewer #3 for the encouragement and extremely useful comments. The manuscript is now revised substantially based on these comments.

General Comments:

The authors present an analysis of the relationship between the TNI and tornadic activity in the United States. The positive correlation between the two is interesting, although the index explains only a small part of the total variance. While disappointing, this is not actually surprising, given that the development of tornadic storms depends on attaining overlap both spatially and temporally between very specific atmospheric conditions: low-level moisture, significant CAPE, large shear (in both the 0-6 km layer and the 0-1 km layer), and low lifting condensation levels. In addition, this overlap has to occur in the presence of some convective inhibition (CIN) to prevent widespread convection, but not so much CIN that no convection can form, and in an area with a mechanism to initiate convection. The juxtaposition of these features is a mesoscale problem that cannot be expected to be captured in long-term averages. The long-term averages can only tell you that these individual conditions exist more often on average and, therefore, their overlap might be expected to also happen more often, but the connection is rather weak given that both spatial and temporal separation is possible even with high averages. This point should come across more clearly in the manuscript.

We fully understand and agree with reviewer #3's point that tornadogenesis is basically a mesoscale problem, and that it requires overlap of very specific local atmospheric conditions. Therefore, we also agree that tornadogenesis is not expected to be adequately captured by large-scale and long-term averaged atmospheric processes. In this study, we simply argue that such overlap of the specific conditions for tornadogenesis may occur more frequently on average during a positive phase of the TNI than during a neutral phase of the TNI. These points are now discussed in section 9 of the revised manuscript.

In addition, it is not clear that the TNI has any correlation with low-level (0-1 km) shear or low LCLs, as these fields were not shown. The fields shown are relevant for supercells but cannot distinguish between those that are tornadic and those that are not. All of these facts conspire to create a relatively weak association between TNI and tornadoes. However, the association is stronger than for some other indices, and at least some physical explanation for this is offered. Thus, I feel the research is worthy of publication with some changes in explanation. Although the changes prescribed probably are not too time consuming, I specified major revision because I would like to see the altered draft.

Now, we add a new plot (Figure 19) for low-level shear between 850mb and 1000mb, which roughly represents the 0-1 km shear. As shown in this figure, low-level vertical wind shear in AM is increased over the central and eastern U.S during both the ten most active tornado years and top ten positive TNI years. This is also well simulated in EXP_TNI – EXP_CLM (Figure

19c). Other important factors such as lifting condensation level height and convective inhibition and their associations with TNI will be explored in a future study. These points are now added in section 9 of the revised manuscript.

Major Comments:

1. Abstract: The terminology "lower-level vertical wind shear" is being used to refer to shear over a layer from 925 mb to 500 mb. This is not considered low-level shear within the severe storms community, where low-level shear refers to shear in the 0-1 km or 0-3 km layers, so the terminology should be changed. Shear up to 500 mb is similar to the 0-6 km shear often used to distinguish environments conducive to supercell activity from those that support only ordinary storms or multicellular storms. Once this deeper-layer shear has established the existence of a supercell regime, the 0-1 km shear and the LCL heights are examined to determine the likelihood of tornadic supercells. Is it possible to examine 0-1 km shear within the current model?

We greatly appreciate this comment. The terminology "lower-level vertical shear" is now changed to "lower-tropospheric vertical wind shear" throughout the revised manuscript. We also examined the low-level vertical wind shear using wind shear between 850mb and 1000mb, which roughly represents the 0~1 km shear. As shown in Figure 19, low-level vertical wind shear in AM is increased over the central and eastern U.S during both the ten most active tornado years and top ten positive TNI years. This is also well simulated in EXP_TNI – EXP_CLM (Figure 19c). Other important factors such as lifting condensation level height and convective inhibition and their associations with TNI will be explored in a future study. These points are now added in section 9 of the revised manuscript.

2. Page 3, Line 1-3: The authors state "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 with U.S. tornado activity in AM." The correlations do not seem very large. As mentioned in the general comments, this is probably because there are many days with strong shear but no CAPE or too much CIN. In other words, the monthly averages could be large without them ever coming together in the right places. Moisture transport is only part of the recipe for CAPE. . Shear is very localized at times; over what area is it being averaged? I do not think these large-scale averages capture the mesoscale nature of these events. Some of these points should be made in the manuscript.

We agree with reviewer #3's point that large-scale and long-term averaged atmospheric conditions alone cannot capture tornadogenesis, which is a mesoscale process and thus requires overlap of very specific and highly localized atmospheric conditions. Therefore, we also agree that tornadogenesis is not expected to be adequately captured by large-scale and long-term averaged atmospheric processes. In this study, we simply argue that such overlap of the specific conditions for tornadogenesis may occur more frequently on average during a positive phase of the TNI than during a neutral phase of the TNI. These points are now discussed in section 9 of the revised manuscript. The lower-tropospheric vertical wind shear used in Table 1 is averaged over the region of 30^{o}N-40^{o}N and 100^{o}W– 80^{o}W. The GoM-to-U.S. moisture transport used in Table 1 is averaged in the region of 25^{o}N-35^{o}N and 100^{o}W–90^{o}W.

3. Page 4, Line 9-10: The authors state "the tropical Pacific SST anomalies in AM are better represented by the TNI index than the conventional ENSO indices…" but it is not clear what they mean by "better represented" given that the ENSO indices are a direct measure of the SST anomalies. I think they must mean "the effects of the tropical SST anomalies in AM are better represented by the TNI index."

According to Tranberth and Stepaniak [2001], the 1st EOF mode of the tropical Pacific SST is very well represented by conventional indices such as Nino3 or Nino3.4. However, they found that the 2nd EOF mode of the tropical Pacific SST is not small and quite significant especially during the ENSO transient period, which usually occurs in March ~ May. Thus, our statement "the tropical Pacific SST anomalies in AM are better represented by the TNI index than the conventional ENSO indices…" is an indirect quotation of Tranberth and Stepaniak [2001]. This statement is now corrected to "the tropical Pacific SST anomalies in AM associated with ENSO are better represented by the TNI index than the conventional ENSO indices…".

4. Page 5, Line 18 and other places: The authors assert that the main influence of the upper-level cyclone over North America is that it advects more cold and dry air to the U.S. While it is important to have cold air aloft, and that is associated with lower heights aloft, another important influence of the cyclone is the development of steep lapse rates and removal of CIN in the region of strong rising motion downstream from the cyclone (owing to differential vorticity advection). This rising motion lifts and destabilizes layers. This is an important part of setting up a good environment for tornadic storms.

We appreciate this very helpful comment. We add this point in section 1 of the revised manuscript. Doswell and Bosart (2001) is referenced.

5. Page 8, Line 23: It is stated that a relatively weak anomalous upper-level cyclone is formed in EXP_LAN, but this is an average over many days of a series of cyclones and anticyclones that moved over the area. Perhaps more precise language is needed to avoid implying that there was a weak cyclone over that area for the entire time period. Figure 7 may indicate that the cyclones on average had a longer dwell time farther east, so the best lifting (downstream from the cyclone) is not collocated with the regions that typically have the best moisture and shear over this period.

We add a paragraph in section 3 to stress this point: "It is worthwhile to point out that all the composite maps and model results in this study should be understood in a long-term averaged sense. For instance, the anomalous upper-level cyclone over the North America shown in Figure 3a is a long-term average over many days during which a series of cyclones as well as anticyclones may have passed over the area."

Minor Comments:

1. *Page 2, Line 2: I'm not sure if these are the correct official numbers, but they do not match those in the link provided. Please double check this before publication.*

The number of tornadoes and casualties are corrected and an updated website is provided.

2. *Page 2, Line 18: add "a" before "conditionally unstable"*

Corrected.

3. *Page 2, Line 20: please change "and" to "and/or" as shear could be associated with a constant wind speed that changes direction with height.*

Corrected.

4. *Page 2, Line 21: Please change "the spinning effect required to form a horizontal vortex tube" to "rotation with respect to a horizontal axis"*

Corrected.

5. *Page 3, Line 7: You should probably specify that you are talking about an upper-level cyclone.*

Corrected.

6. *Page 3, Line 8: "bring" should be "brings"*

Corrected.

7. *Page 3, Line 12: add "flow" after "southeasterly"*

Corrected.

8. *Page 5, Lines 4-5: Please change "The tornado-days index is on the other hand put little weight" to "The tornado-days index, on the other hand, puts little weight…"*

Corrected.

9. *Page 5, Line 7: remove "and used"*

Corrected.

10. *Page 6, line 8: "index" is not needed after TNI given that it is already part of the acronym*

Corrected.

11. *p. 6, line 13-14: It is said in various places that SSTs indicate "cooling" or "warming," but this terminology seems strange to me. Cooling or warming implies a rate of change in time, but you are showing SST anomalies at only one time. These plots seem to indicate "colder than normal" or "warmer than normal" but not "cooling" or "warming."*

Throughout the revised manuscript, “cooling” and “warming” are now changed to “colder than normal SSTs” and “warmer than normal SSTs”, respectively.

12. *Figure 10 has two "a" panels rather than one "a" and one "b"*

Corrected.

13. *Page 13, line 15: "Hareld" should be "Harold"*

Corrected.

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

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

[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

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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

The record-breaking U.S. tornado outbreaks in the spring of 2011 prompt the need to identify long-term climate signals that could potentially provide seasonal predictability for intense U.S. tornado outbreaks. Here we use both observations and model experiments to show that a positive phase of Trans-Niño, characterized by colder than normal sea surface temperatures (SSTs) in the central tropical Pacific and warmer than normal SSTs in the eastern tropical Pacific, may be one such climate signal. Warmer-than-normal SSTs in the eastern tropical Pacific increase convection locally, but also contribute to suppressing convection in the central tropical Pacific. This in turn works constructively with colder than normal SSTs in the central tropical Pacific to force a strong and persistent 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-tropospheric 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 warmer than normal SSTs 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 1,084 tornadoes and 538 tornado-related fatalities were confirmed in the U.S., making 2011 one of the deadliest tornado years in U.S. history [http://www.spc.noaa.gov/climo/online/monthly/newm.html#2011]. 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 1). However, due to numerous known deficiencies in the SWD, including improvements in tornado detection technology, increased eyewitness reports due to population increase, and changes in damage survey procedures 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). In this study, only the intense U.S. tornadoes (i.e., from F3 to F5 in the Fujita-Pearson scale) are selected and used since intense and long-lived tornadoes are less likely to be affected by, although not completely free from, the known issues in the tornado database.

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), a conditionally unstable atmosphere with high convective available potential energy is formed. The lower-tropospheric vertical wind shear associated with the upper-level westerly and lower-level southeasterly winds (i.e., wind speed increasing and/or wind direction changing with height) provides the rotation with respect to a horizontal axis. 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 (Lemon and Doswell 1979; Doswell and Bosart 2001). Consistently, both the moisture transport from the GoM to the U.S. and the lower-tropospheric vertical wind shear in the central and eastern U.S. are positively correlated with the number of intense U.S. tornadoes in AM (Table 1).

The Pacific - North American (PNA) pattern in boreal winter and spring is linked to the large-scale differential advection and the lower-tropospheric vertical wind shear in the central and eastern U.S (Horel and Wallace 1981; Walalce and Gutzler 1981; Barnston and Livezey 1987). During a negative phase of the PNA, an anomalous upper-level cyclone is formed over North America that brings 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. The upper-level cyclone also contributes to the development of steep lapse rates and removal of convective inhibition in the region of strong rising motion downstream from the cyclone (due to differential vorticity advection) and thus sets up a favorable environment for tornadogenesis (e.g., Doswell and Bosart 2001).

Additionally, the lower-tropospheric 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 flow. 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 (Lau and Lim 1984; 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 (Alexander and Scott 2002). 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 highly correlated with U.S. tornado activity in AM (Table 1). Consistently, earlier studies reported that the connectivity between the El Niño-Southern Oscillation (ENSO) and U.S. tornado activity is quite weak (Marzaban and Schaeffer 2001; Cook and Schafer 2008). Currently, seasonal forecast skill for intense U.S. tornado outbreaks, such as occurred in 2011, has not been demonstrated.

Interestingly, among the long-term climate patterns considered in Table 1, the number of U.S. tornadoes in AM is more strongly correlated with the Trans-Nino (TNI) than any other climate pattern. 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 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 patterns in AM associated with ENSO 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 clear why U.S. tornado activity in AM is more strongly correlated with the TNI index than 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. U.S. Tornado index

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, only the intense U.S. tornadoes in AM during 1950-2010 from the SWD are selected and used in this study. The number of intense U.S. tornadoes is used, after detrending, as the primary diagnostic index (Figure 2b). Another tornado metric used in this study is the intense U.S. tornado-days (Figure 2c and d), which is obtained by counting the number of days in which more than a threshold number of intense tornadoes occurred (see Verbout et al. 2006). The threshold number selected in this case is three and above, which roughly represents the upper quartile in the number of intense U.S. tornadoes in a given day of AM during 1950-2010. In general, the tornado count index is sensitive to big tornado outbreak days, such as April 3, 1974 during which 60 intense tornadoes occurred over the U.S. The tornado-days index, on the other hand, puts little weight on big tornado days. Since these two tornado indices are complementary to each other, it is beneficial to use both of these indices. The two tornado indices are further detrended by using a simple least squares linear regression.

3. Observed relationship between TNI and U.S. tornado activity

It is noted that the historical time series for the number of intense (from F3 to F5 in the Fujita-Pearson scale) tornadoes is characterized by intense tornado outbreak years, such as 1974, 1965 and 1957, embedded amongst much weaker amplitude fluctuations (Figure 2a and b). Since the majority of tornado-related fatalities occur during those extreme outbreak years, here we focus our attention to those extreme years and associated climate signals. Therefore, we ranked the years from 1950 to 2010 (61 years in total) based on the number of intense U.S. tornadoes in AM.

The top ten extreme tornado outbreak years are characterized by an anomalous upper-level cyclone over North America that advects more cold and dry air to the U.S. (Figure 3a), increased Gulf-to-U.S. moisture transport (Figure 3b) and increased lower-tropospheric vertical wind shear over the U.S. (Figure 3c), whereas the bottom ten years are associated with an anomalous upper-level anticyclone over North America (Figure 3d), decreased Gulf-to-U.S. moisture transport (Figure 3e) and decreased lower-tropospheric vertical wind shear over the central and eastern U.S. (Figure 3f). It is worthwhile to point out that all the composite maps and model results shown in this study should be understood in a long-term averaged sense. For instance, the anomalous upper-level cyclone over the North America shown in Figure 3a is a long-term average over many days during which a series of cyclones as well as anticyclones may have passed over the area. Note that if the tornado ranking is redone based on the intense U.S tornado-days in AM, 1998 in the top ten list is replaced by 1960, but other top nine years remain in the top ten (not shown).

As in the top ten extreme tornado outbreak years, the top ten positive TNI years are also characterized by an anomalous upper-level cyclone over North America (Figure 4a), increased Gulf-to-U.S. moisture transport (Figure 4b) and increased lower-tropospheric vertical wind shear over the U.S. (Figure 4c). Due to these large-scale atmospheric conditions, the number of intense U.S. tornadoes in AM during the top ten positive TNI years is nearly doubled from that during the ten neutral TNI years (Figure 5a and b). Consistent with these findings, among the top ten extreme tornado outbreak years, seven years including the top three are identified with a positive phase (i.e., within the upper quartile) TNI (i.e., normalized SST anomalies are larger in the Niño-1+2 than in Niño-4 region) (Table 2). 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). The composite SST anomalies for those five positive phase TNI years transitioning from a La Niña are characterized by colder than normal SSTs in the central tropical Pacific (CP) and warmer than normal SSTs in the eastern tropical Pacific (EP) (Figure 6a) as in the composite SST anomalies for the top ten positive TNI years (Figure 6b). If the top ten extreme tornado outbreak years are averaged together, the composite SST anomalies are still characterized by a positive phase TNI (i.e., normalized SST anomalies are larger in the Niño-1+2 than in Niño-4 region), although the colder than normal SST anomalies in CP are nearly canceled out (Figure 6c).

In the bottom ten years (Table 3), on the other hand, 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). This result suggests that a negative phase of the TNI neither decreases nor increases the number of intense U.S. tornadoes in AM, and thus partly explains why the overall correlation between the TNI and the number of intense U.S. tornadoes in AM is not high. Consistently, the number of intense U.S. tornadoes in AM during the top ten negative TNI years is not much changed from that during the ten neutral TNI years (Figure 5b and c). 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).

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) (Figure 7a). Similarly, 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) (Figure 7b).

In summary, observations seem to indicate that a positive phase of the TNI (i.e., normalized SST anomalies are larger in the Niño-1+2 than in Niño-4 region) is linked to increased U.S. tornado activity in AM, whereas either 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 not linked to increased U.S. tornado activity in AM.

4. Model Experiments

To explore the potential link between the tropical Pacific SST anomaly patterns identified in the previous section (Figure 6 and 7) 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. 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 for studying ENSO teleconnection to the tropical North Atlantic region (Lee et al. 2008; Lee et al. 2010).

Six sets of ensemble runs are performed (Table 4). 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 are considered in this case (Figure 6a). Two experiments similar to EXP_TNI are carried out by prescribing the SSTs in the tropical Pacific region with the composite SSTs of the top ten positive TNI years (Figure 6b) for EXP_TN1, and the top ten most extreme tornado years (Figure 6c) for EXP_TN2. 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 (Figure 7a) for EXP_LAN, and the four years in the bottom ten years with an El Niño transitioning (Figure 7b) for EXP_ELN.

5. Simulated impact of TNI on tornadic environments

In EXP_TNI (Figure 8), 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-tropospheric 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. All of these large-scale atmospheric conditions are also well reproduced in both EXP_TN1 and EXP_TN2 (Figure 9).

In EXP_ELN (Figure 10d, e and f), on the other hand, the Gulf-to-U.S. moisture transport is neither increased nor decreased. The lower-tropospheric vertical wind shear is slightly decreased over the central and eastern U.S. mainly due to a weak anomalous upper-level anticyclone formed (in a long-term and ensemble averaged sense) over North America. In EXP_LAN (Figure 10a, b and c), a relatively weak anomalous upper-level cyclone is formed, and thus the lower-tropospheric vertical wind shear is slightly increased. However, the Gulf-to-U.S. moisture is not increased.

In summary, these model results support the hypothesis that a positive phase of the TNI with colder than normal SSTs in CP and warmer than normal SSTs in EP enhances the large-scale differential advection in the central and eastern U.S. and increases the lower-tropospheric 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 (i.e., neutral phase TNI), consistent with the observations.

6. CP- versus EP-forced teleconnection

The model results strongly suggest that colder than normal SSTs in CP and warmer than normal SSTs in EP may have a constructive influence on the teleconnection pattern that strengthens the large-scale differential advection and lower-tropospheric vertical wind shear over the central and eastern U.S. To better understand how the real atmosphere with moist diabatic processes responds to colder than normal SSTs in CP and warmer than normal SSTs in EP, two sets of additional model experiments (EXP_CPC and EXP_EPW) are performed (Table 4). 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. Note that climatological SSTs are prescribed in the eastern Pacific region (15°S–15°N; 110°W-coast of the Americas) for EXP_CPC and in the western and central tropical Pacific region (15°S–15°N; 120°E - 110°W) for EXP_EPW.

In EXP_CPC (Figure 11a, b and c), 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 11a). 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 11b). The lower-tropospheric 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 winds (Figure 11c).

Surprisingly, the Rossby wave train forced by warmer than normal SSTs in EP (EXP_EPW) is very similar to that in EXP_CPC (Figure 11d). Consistently, both the Gulf-to-U.S. moisture transport and the lower-tropospheric vertical wind shear over the central and eastern U.S. are also increased in EXP_EPW as in EXP_CPC and EXP_TNI (Figure 11e and f). A question arises as to why the teleconnection pattern forced by warmer than normal SSTs in EP is virtually the same as that forced by colder than normal SSTs 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 12c). This suggests that increased convection in EP associated with the increased local SSTs suppresses convection in CP and that in turn forces a negative phase PNA-like pattern. Therefore, these model results confirm that colder than normal SSTs in CP and warmer than normal SSTs in EP do have constructive influence on the teleconnection pattern that strengthens the large-scale differential advection and lower-tropospheric vertical wind shear over the central and eastern U.S. The model results also suggest that colder than normal SSTs in CP with neutral SST anomalies in EP or warmer than normal SSTs in EP with neutral SST anomalies in CP can also strengthen the large-scale differential advection and lower-tropospheric vertical wind shear over the central and eastern U.S.

An apparently important question is why warmer than normal SSTs 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., Kasahara and da Silva Dias 1986; Wang and Xie 1996; 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 a potential explanation as to why the Rossby wave train in EXP_EPW is not directly forced in EP (Figure 13).

Another related and important question is how increased convection in EP associated with the increased local SSTs suppresses convection in CP remotely. Although answering this question requires a more extensive study, one plausible explanation is that the warmer than normal SSTs in EP induces a global average warming of the tropical troposphere via a fast tropical teleconnection mechanism (e.g., Chiang and Sobel 2002), and thus increases atmospheric static stability and decreases convection over CP and other tropical regions of normal SSTs. A similar argument was previously used in Lee et al. (2011) to explain reduced deep convection in the tropical Atlantic in response to warmer than normal SSTs in the tropical Pacific. Another similar argument, but in a different context, is the "upped-ante mechanism", which is often used to explain anomalous descent motions neighboring warm SST anomalies in the eastern and central Pacific Ocean during El Niño (Su and Neelin 2002; Neelin et al. 2003).

7. Implications for a seasonal outlook for extreme U.S. tornado outbreaks

The conclusion so far is that a positive phase of the TNI, characterized by colder than normal SSTs in CP and warmer than normal SSTs in EP, strengthens the large-scale differential advection and lower-tropospheric vertical wind shear in the central and eastern U.S., and thus provides favorable large-scale atmospheric conditions for major tornado outbreaks over the U.S. In this sense, a positive phase of the TNI may be an optimal ENSO pattern that increases the chance for major U.S. tornado outbreaks. However, the TNI explains only up to 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 positive phase 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). In other words, the 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.

Nevertheless, seven of the ten most extreme tornado outbreak years during 1950-2010 including the top three years are characterized by a strongly positive phase of the TNI (Table 2).

A practical implication of this result is that a seasonal outlook for extreme U.S. tornado outbreaks may be achievable if a seasonal forecasting system has significant skill in predicating the TNI and associated teleconnections to the U.S. Obviously, before we can achieve such a goal, there remain many crucial scientific questions to be addressed 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.

8. U.S. Tornado Outbreaks in 2011

A positive phase of the TNI prevailed during AM of 2011 with colder than normal SSTs in CP and warmer than normal SSTs in EP (Figure 14). 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 15a), the Gulf-to-US moisture was greatly increased (Figure 15b), and the lower-tropospheric vertical wind shear was increased over the central U.S. (Figure 15c), 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 4). As summarized in Figure 16, the model results are consistent with the observations, although the anomalous Gulf-to-US moisture transport is weaker in the model experiment. Thus, 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-tropospheric vertical wind shear in the central and eastern U.S.

A distinctive feature in the 2011 TNI event is warmer than normal SSTs in WP (Figure 14). Further experiments (Table 4) suggest that the warmer than normal SSTs in WP indirectly suppress convection in CP, and thus work constructively with the colder than normal SSTs in CP to force a strong and persistent negative phase PNA-like pattern (Figure 16 and 17).

9. Discussions

Tornadogenesis is basically a mesoscale problem that requires overlap of very specific and highly localized atmospheric conditions. Therefore, it is not expected to be adequately captured by large-scale and long-term averaged atmospheric processes. In this study, we simply argue that such overlap of the specific conditions for tornadogenesis may occur more frequently on average during a positive phase of the TNI than during a neutral phase of the TNI. In addition to the large-scale atmospheric conditions explored in this study, there are other specific atmospheric conditions that distinguish tornadic supercells from non-tornadic supercells. One such condition is increased low-level (0~1 km) vertical wind shear. As shown in Figure 19a and b, low-level vertical wind shear in AM is increased over the central and eastern U.S. during both the ten most active tornado years and top ten positive TNI years. This is also well simulated in EXP_TNI (Figure 18c). Other important factors such as lifting condensation level height and convective inhibition and their associations with TNI are to be explored in the future studies.

One of the caveats in this study, as in any tornado related climate research, is an artificial inhomogeneity in the tornado database. Eyewitness reports are important sources for tornado count, which can be affected by population growth and migration. Additionally, tornado rating is largely based on structural damage - wind speed relationship, which can change with time and case-by-case because every particular tornado - structure interaction is different in detail. For these and other reasons, the historical time series of the tornado database cannot be completely objective or consistent over time (Doswell et al. 2009). In this study, only the intense U.S. tornadoes (F3 - F5) are selected and used since intense and long-lived tornadoes are less likely to be affected by, although not completely free from, such issues in the tornado database. An alternative approach is to develop and use a proxy tornado database, which can be derived from tornadic environmental conditions in atmospheric reanalysis products. Results from recent studies that used such an approach were very promising (Brooks et al. 2003; Tippett et al. 2012).

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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 tornadoes in AM during 1950-2010. The values in parenthesis are those with the intense U.S. tornado-days 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[a].

Index	DJF	FMA	AM
Gulf-to-U.S. moisture transport	0.08 (0.05)	0.20 (0.14)	0.40 (0.36)
Lower-level vertical wind shear	0.06 (0.04)	0.15 (0.25)	0.34 (0.30)
GoM SST	0.15 (0.15)	0.21 (0.16)	0.20 (0.19)
Niño-4	-0.22 (-0.19)	-0.20 (-0.18)	-0.19 (-0.18)
Niño-3.4	-0.13 (-0.11)	-0.13 (-0.12)	-0.11 (-0.11)
Niño-1+2	0.02 (0.03)	0.11 (0.11)	0.15 (0.13)
TNI	0.28 (0.26)	0.29 (0.28)	0.33 (0.29)
PNA	-0.05 (-0.02)	-0.10 (-0.06)	-0.20 (-0.16)
PDO	-0.12 (-0.09)	-0.10 (-0.11)	-0.14 (-0.20)
NAO	-0.01 (-0.07)	-0.10 (-0.14)	-0.18 (-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°N – 40°N and 100°W – 80°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.

Table 2. The total of 61 years from 1950 to 2010 are ranked based on the detrended number of intense U.S. tornadoes in AM. The top ten extreme U.S. tornado outbreak years are listed with ENSO phase in spring and TNI index in AM for each year. Strongly positive (i.e., the upper quartile) and negative (i.e., the lower quartile) TNI index values are in bold and italic, respectively.

Ranking	Year	ENSO phase in spring	TNI index (detrended)
1	1974	La Niña persists	**1.30 (1.48)**
2	1965	La Niña transitions to El Niño	**1.39 (1.54)**
3	1957	La Niña transitions to El Niño	**0.57 (0.69)**
4	1982	El Niño develops	*-1.11* (*-0.89*)
5	1973	El Niño transitions to La Niña	-0.42 (-0.24)
6	1999	La Niña persists	**0.47 (0.75)**
7	1983	El Niño decays	**1.86 (2.08)**
8	2003	El Niño decays	*-1.24* (*-0.94*)
9	2008	La Niña decays	**1.41 (1.73)**
10	1998	El Niño transitions to La Niña	**1.69 (1.97)**

Table 3. The total of 61 years from 1950 to 2010 are ranked based on the detrended number of intense U.S. tornadoes in AM. The bottom ten years are listed with ENSO phase in spring and TNI index in AM for each year. Strongly positive (i.e., the upper quartile) and negative (i.e., the lower quartile) TNI index values are in bold and italic, respectively.

Ranking	Year	ENSO phase in spring	TNI index (detrended)
52	1958	El Niño decays	-0.61 (-0.49)
53	1955	La Niña persists	-0.27 (-0.16)
54	2001	La Niña decays	0.21 (0.50)
55	1986	El Niño develops	-0.39 (-0.16)
56	1988	El Niño transitions to La Niña	-0.37 (-0.13)
57	1987	El Niño persists	0.10 (0.34)
58	1992	El Niño decays	0.21 (0.47)
59	1952	Neutral	-0.67 (-0.57)
60	1951	La Niña transitions to El Niño	-0.31 (-0.22)
61	1950	La Niña persists	**0.77 (0.86**)

Table 4. Prescribed SSTs in the tropical Pacific region for each model experiment. All model experiments are initiated from April of the prior year to December of the modeling year. For instance, in EXP_TNI, the model is integrated for 21 months starting in April using the composite April SSTs of 1956, 1964, 1973, 1998, and 2007.

Experiments	Prescribed SSTs in the tropical Pacific region
EXP_CLM	Climatological SSTs are prescribed in the tropical Pacific region (15°S–15°N; 120°E-coast of the Americas).
EXP_TNI	Composite SSTs of the five positive phase TNI years transiting from a La Niña identified among the ten most active U.S. tornado years (1957, 1965, 1974, 1999, and 2008) are prescribed in the tropical Pacific region. Two similar experiments are carried out by prescribing the SSTs in the tropical Pacific region with the composite SSTs of the top ten positive TNI years for EXP_TN1, and the top ten most extreme tornado years for EXP_TN2.
EXP_LAN	Composite SSTs of the four years with a La Niña transitioning (1950, 1951, 1955 and 2001) identified among the ten least active U.S. tornado years are prescribed in the tropical Pacific region.
EXP_ELN	Composite SSTs of the four years with an El Niño transitioning (1958, 1987, 1988 and 1992) identified among the ten least active U.S. tornado years are prescribed in the tropical Pacific region
EXP_CPC	Same as EXP_TNI except that the composite SSTs are prescribed only in the western and central tropical Pacific region (15°S–15°N; 120°E - 110°W), while in the eastern Pacific region (15°S–15°N; 110°W-coast of the Americas) climatological SSTs are prescribed.
EXP_EPW	Same as EXP_TNI except that the composite SSTs are prescribed only in the eastern tropical Pacific region (15°S–15°N; 110°W-coast of the Americas), while in the western and central tropical Pacific region (15°S–15°N; 120°E - 110°W) climatological SSTs are prescribed.
EXP_011	SSTs for 2010-2011 are prescribed in the tropical Pacific region.
EXP_WPW	Same as EXP_011 except that the SSTs for 2010-2011 are prescribed only in the western Pacific region (15°S–15°N; 120°E - 180°).

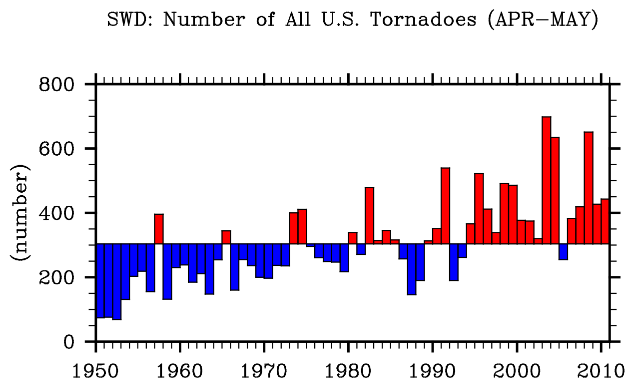

Figure 1. The number of all (F0 – F5) U.S. tornadoes for the most active tornado months of April and May (AM) during 1950-2010 obtained from SWD.

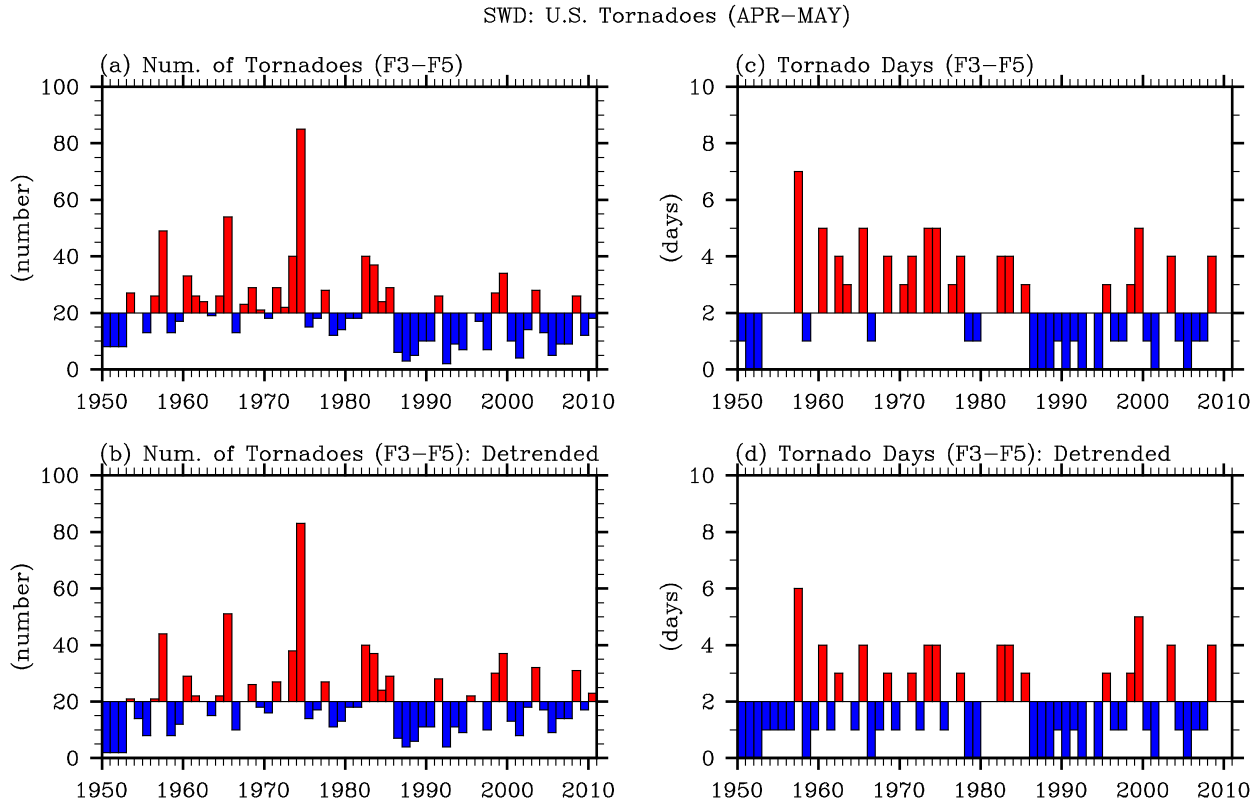

Figure 2. (a) The number of intense (F3 – F5) U.S. tornadoes and (c) the intense tornado-days for the most active tornado months of April and May (AM) during 1950-2010 obtained from SWD. The intense U.S. tornado-days is obtained by counting the number of days in which more than three intense tornadoes occurred. The detrended number of intense tornadoes and the detrended intense tornado-days are shown in (b) and (d), respectively.

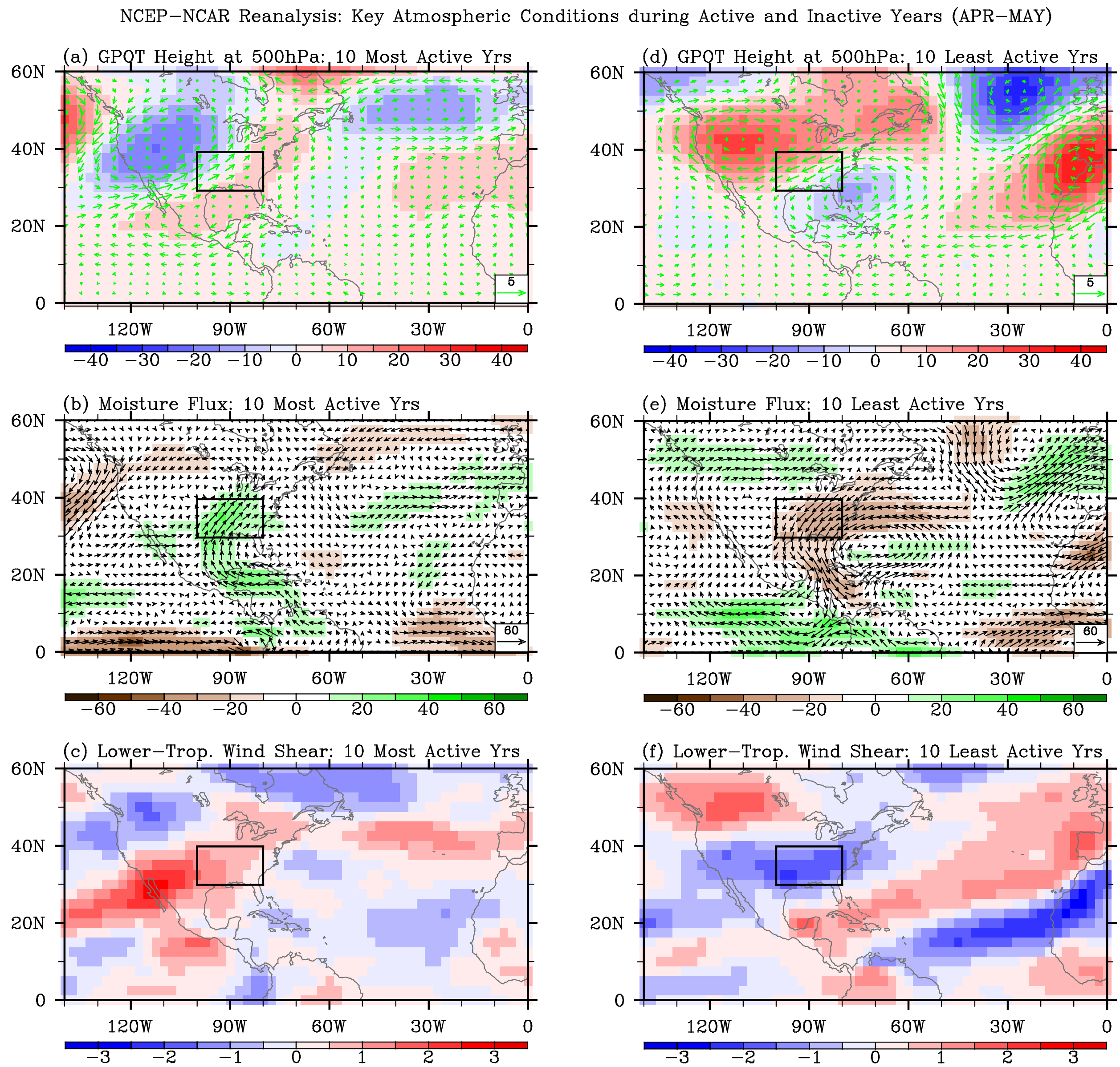

Figure 3. Anomalous geopotential height and wind at 500 hPa, moisture transport and lower-tropospheric (500 hPa – 925 hPa) vertical wind shear for the ten most active U.S. tornado years (a, b and c) and the ten least active U.S. tornado years (d, e and f) in AM during 1950-2010 obtained from NCEP-NCAR 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. The values of the 90% confidence interval averaged over the North America (30^oN-50^oN, and 120^oW-70^oW) are 1.0 (1.0), 14 (16) and 1.1 (1.3) for a (d), b (e) and c (f), respectively.

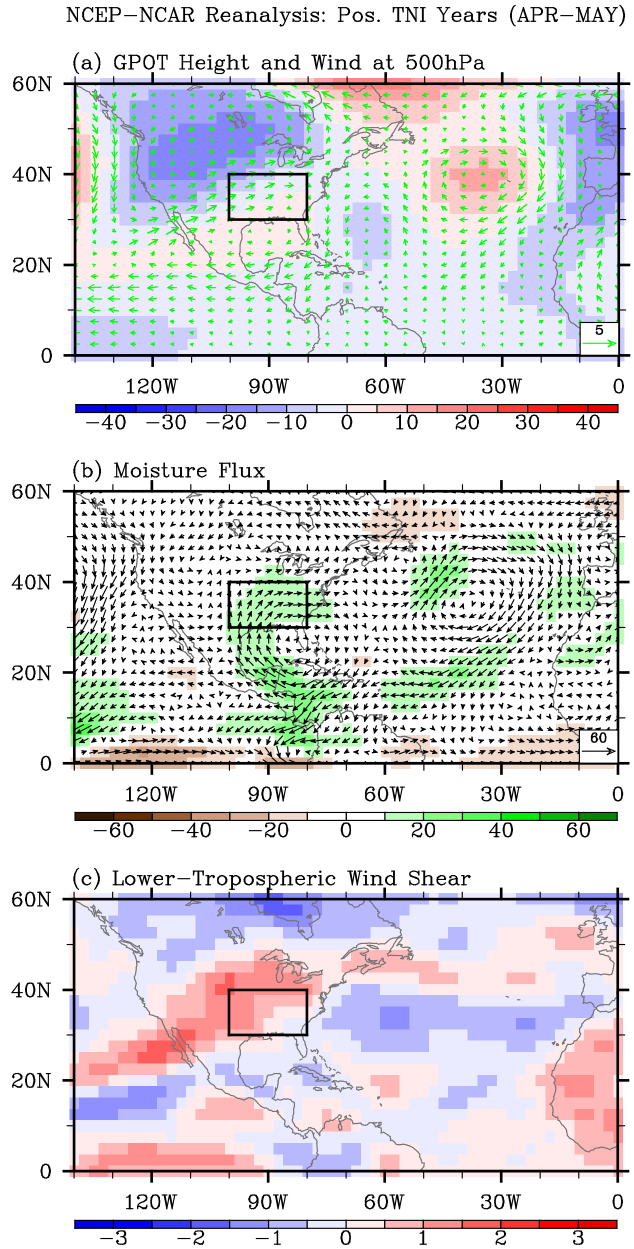

Figure 4. Anomalous (a) geopotential height and wind at 500 hPa, (b) moisture transport and (c) lower-tropospheric (500 hPa – 925 hPa) vertical wind shear for the top ten positive TNI years in AM during 1950-2010 obtained from NCEP-NCAR reanalysis. The units are kg $m^{-1}sec^{-1}$ for moisture transport, m for geopotential height, and m s^{-1} for wind and wind shear. The small box in (a) - (c) indicates the central and eastern U.S. region frequently affected by intense tornadoes. The values of the 90% confidence interval averaged over the North America (30^oN-50^oN, and 120^oW-70^oW) are 0.9, 14 and 1.2 for a, b and c, respectively.

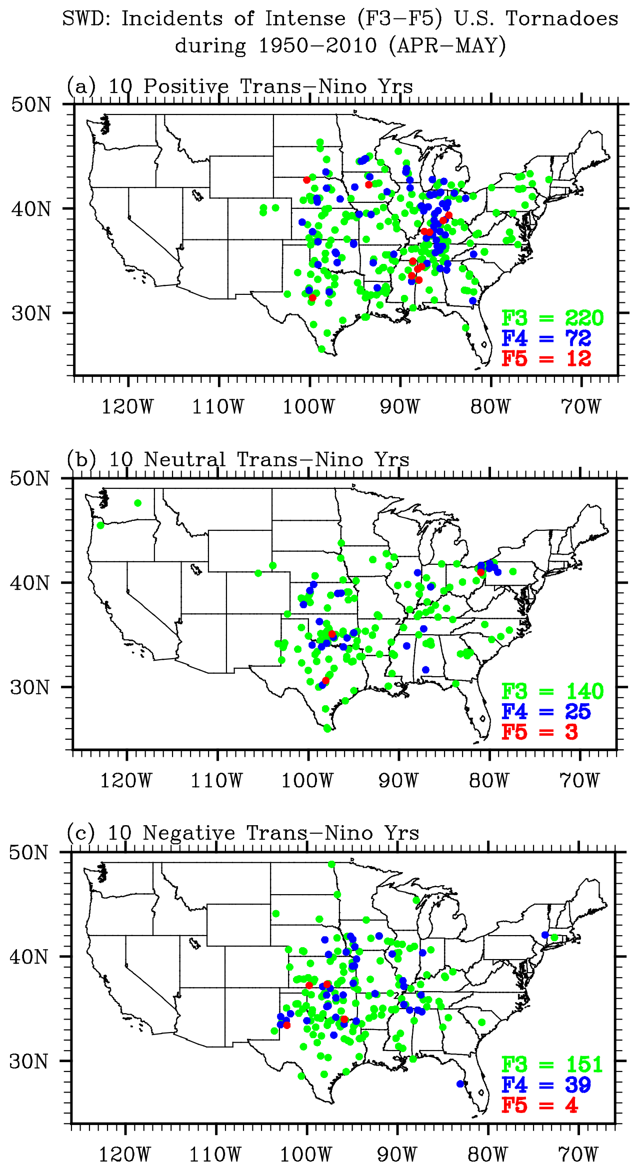

Figure 5. Incidents of intense (F3-F5) U.S. tornadoes in AM for (a) the top ten positive TNI year, (b) ten neutral TNI years, and (c) the top ten negative TNI years during 1950-2010 obtained from SWD. Green color is for F3, blue color for F4 and red color for F5 tornadoes.

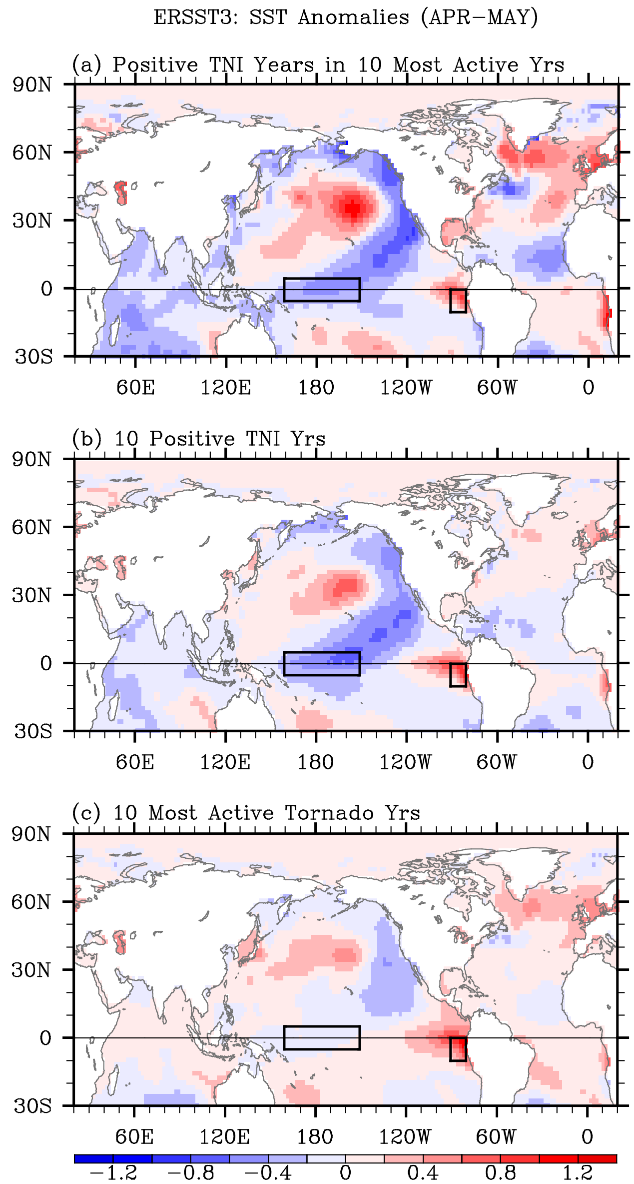

Figure 6. Composite SST anomalies in AM, obtained from ERSST3, for (a) the five positive TNI years transitioning from a La Niña identified among the ten most active U.S. tornado years in AM during 1950-2010, and for (b) the top ten positive TNI years and (c) the ten most active U.S. tornado years in AM during 1950-2010. Thick black rectangles indicate the Niño-4 (5°N - 5°S; 160°E - 150°W) and Niño-1+2 (10S° - 0°; 90°W - 80°W) regions. The values of the 90% confidence interval averaged over the tropical Pacific (15°S-15°N, and 120°E-coast of the Americas) are 0.4, 0.3 and 0.3 for a, b and c, respectively.

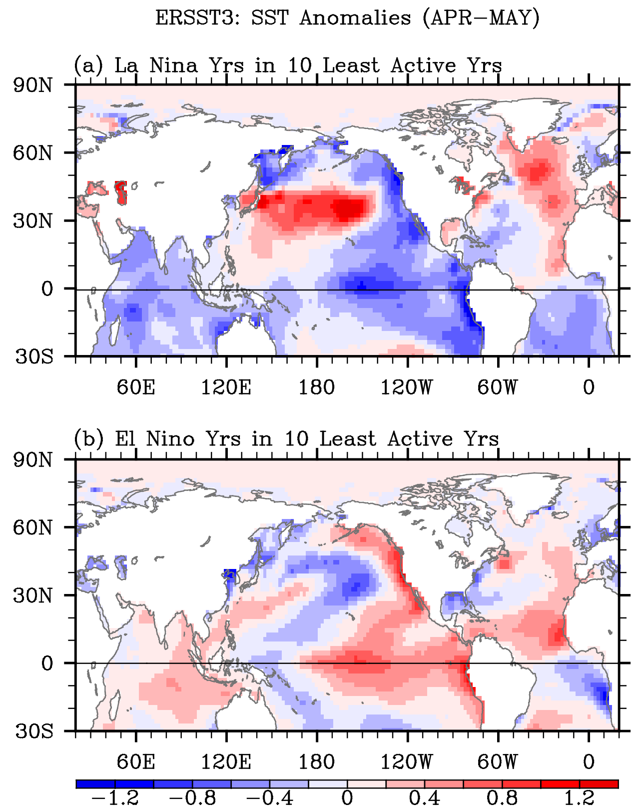

Figure 7. Composite SST anomalies in AM, obtained from ERSST3, for (a) the four years with a La Niña transitioning and (b) the four years with an El Niño transitioning identified among the ten least active U.S. tornado years in AM during 1950-2010. The values of the 90% confidence interval averaged over the tropical Pacific (15^{o}S-15^{o}N, and 120^{o}E-coast of the Americas) are 0.4 and 0.5 for a and b, respectively.

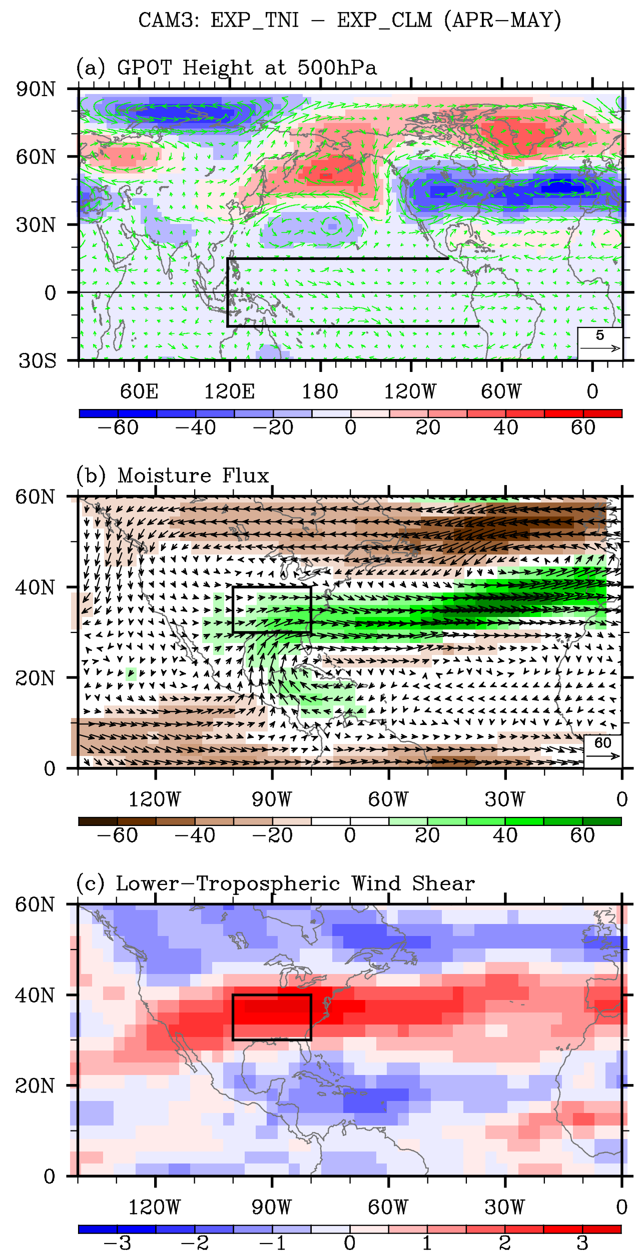

Figure 8. Simulated anomalous (a) geopotential height and wind at 500 hPa, (b) moisture transport and (c) lower-tropospheric (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_TNI – EXP_CLM. The units are kg m^{-1} sec^{-1} for moisture transport, m for geopotential height, and m s^{-1} 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. The values of the 90% confidence interval averaged over the North America (30°N-50°N, and 120°W-70°W) are 1.5, 19 and 1.2 for a, b and c, respectively.

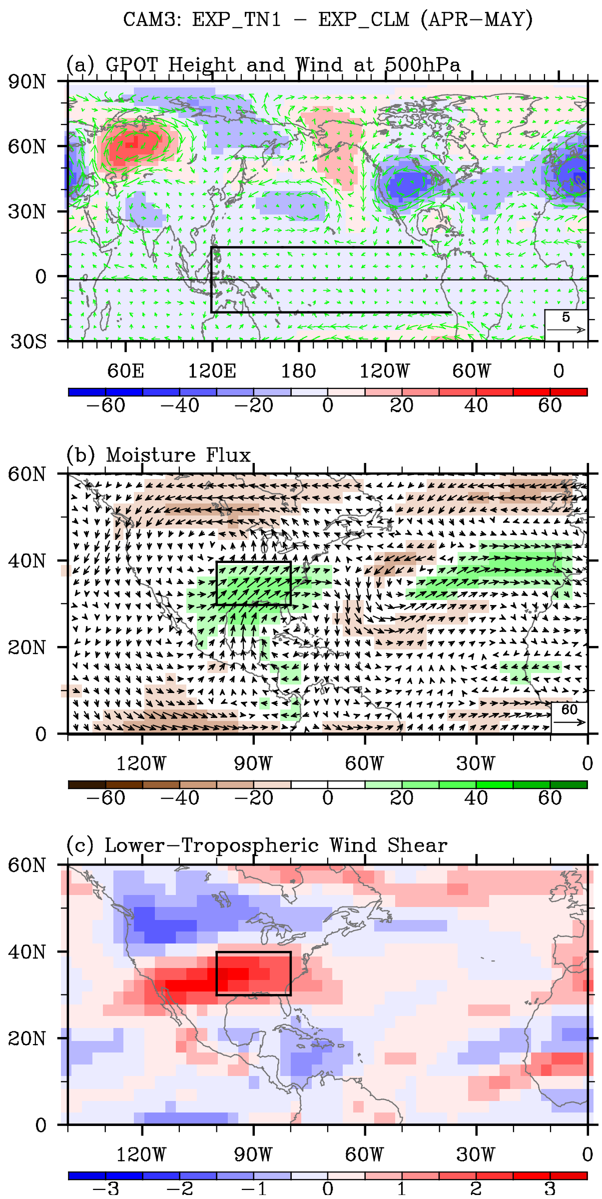

Figure 9. Simulated anomalous geopotential height and wind at 500, moisture transport and (c) lower-tropospheric (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_TN1 – EXP_CLM (a, b and c) and EXP_TN2 – EXP_CLM (d, e and f). The unit is kg m^{-1} sec^{-1} for moisture transport, m for geopotential height, and m s^{-1} for wind and wind shear. Thick black lines in (a) and (d) indicate the tropical Pacific region 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. The values of the 90% confidence interval averaged over the North America (30^{o}N-50^{o}N, and 120^{o}W-70^{o}W) are 1.7 (1.6), 26 (26) and 1.3 (1.3) for a (d), b (e) and c (f), respectively.

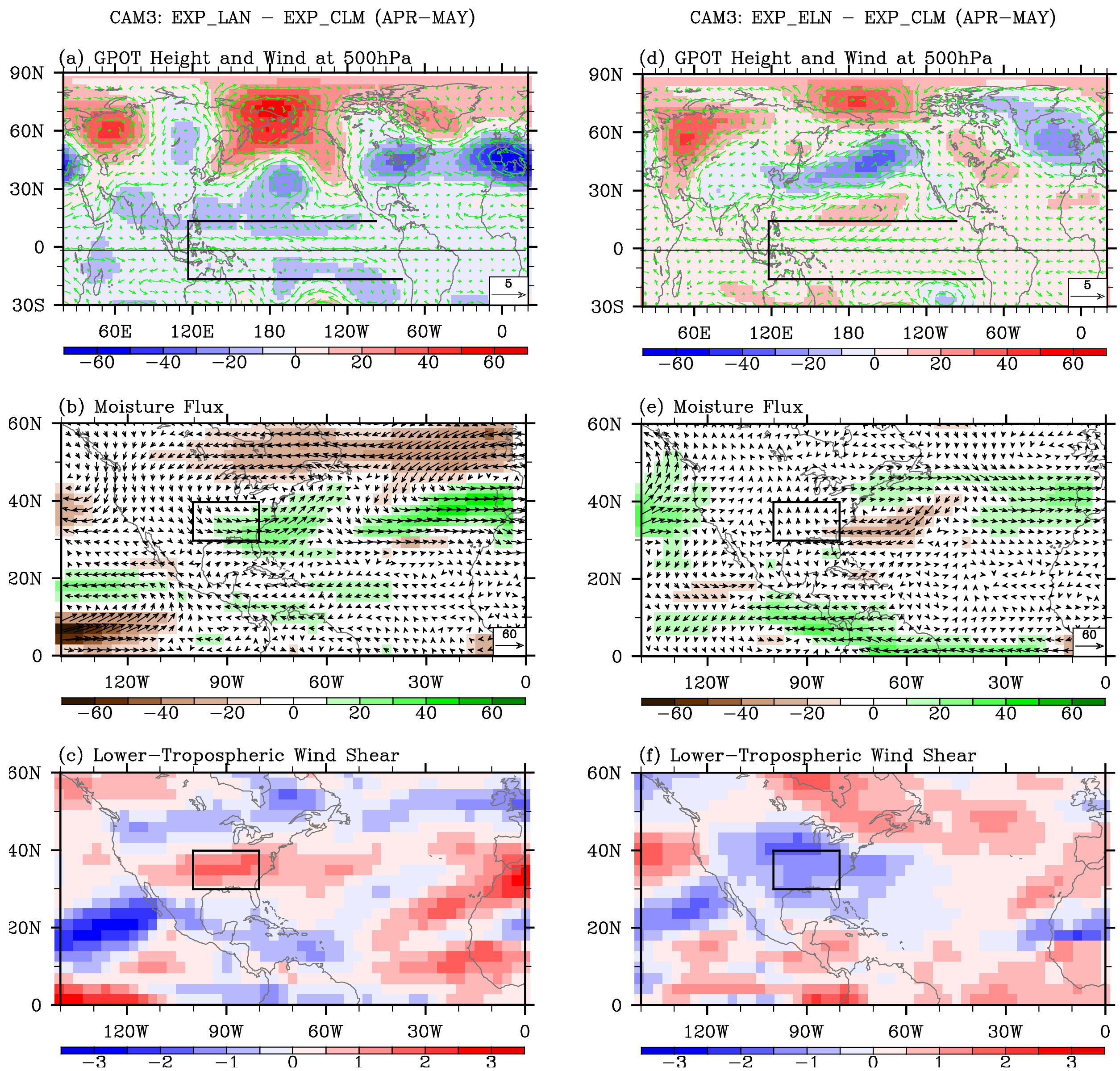

Figure 10. Simulated anomalous geopotential height and wind at 500, moisture transport and (c) lower-tropospheric (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_LAN – EXP_CLM (a, b and c) and EXP_ELN – EXP_CLM (d, e and f). The unit is kg m^{-1} sec^{-1} for moisture transport, m for geopotential height, and m s^{-1} for wind and wind shear. Thick black lines in (a) and (d) indicate the tropical Pacific region 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. The values of the 90% confidence interval averaged over the North America (30^{o}N-50^{o}N, and 120^{o}W-70^{o}W) are 1.7 (1.4), 25 (22) and 1.3 (1.1) for a (d), b (e) and c (f), respectively.

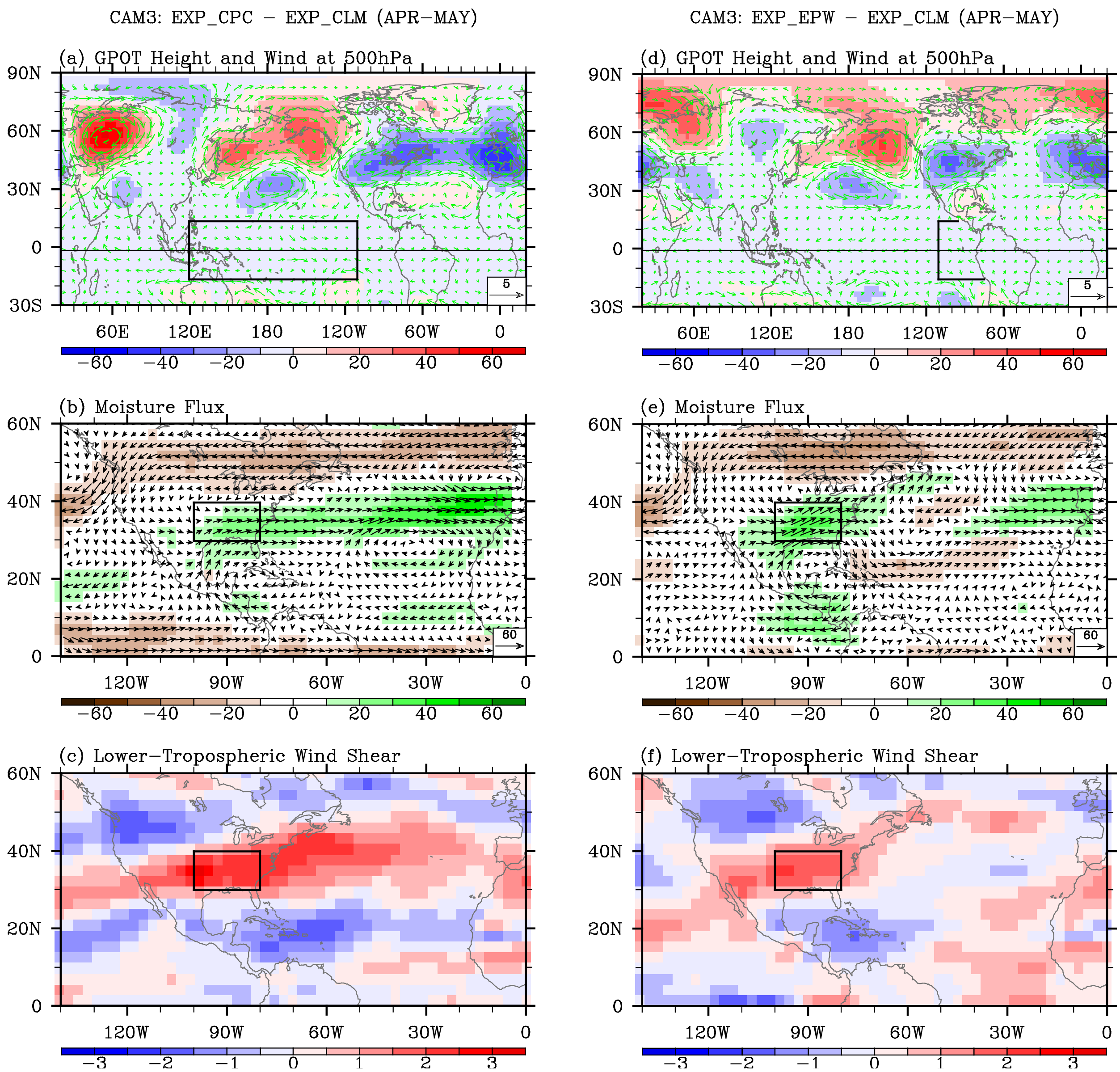

Figure 11. Simulated anomalous geopotential height and wind at 500 hPa, moisture transport, and lower-tropospheric (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_CPC – EXP_CLM (a, b and c), and EXP_EPW – EXP_CLM (d, e and f). The units are kg m^{-1} sec^{-1} for moisture transport, m 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. The values of the 90% confidence interval averaged over the North America (30°N-50°N, and 120°W-70°W) are 1.6 (1.5), 22 (21) and 1.2 (1.2), for a (d), b (e) and c (f), respectively.

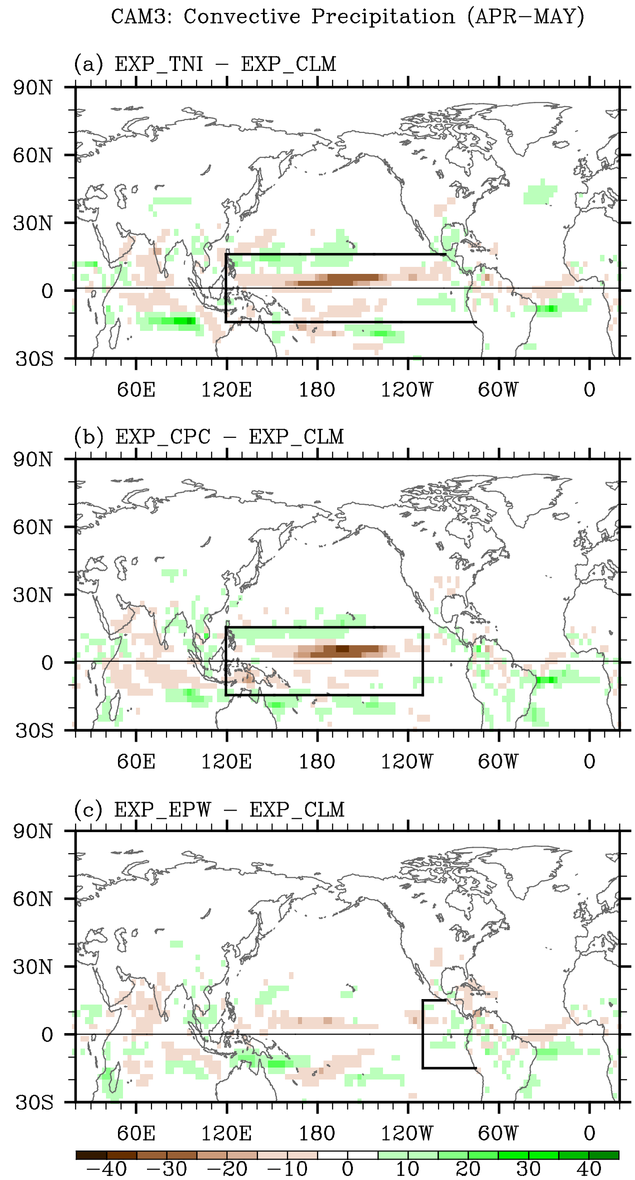

Figure 12. Simulated anomalous convective precipitation rate in AM obtained from (a) EXP_TNI – EXP_CLM, (b) EXP_CPC – EXP_CLM, and (c) EXP_EPW – EXP_CLM. The unit is mm day^{-1}. Thick black lines in (a) - (c) indicate the tropical Pacific region where the model SSTs are prescribed. The values of the 90% confidence interval averaged over the tropical Pacific (15^{o}S-15^{o}N, and 120^{o}E-coast of the Americas) are 4.7, 5.2 and 5.1 for a, b and c, respectively.

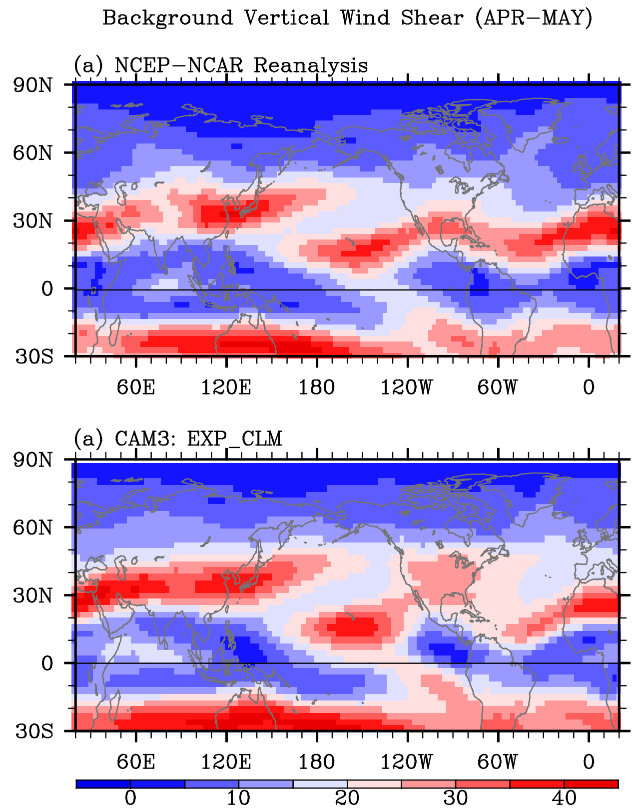

Figure 13. Background (climatological) vertical wind shear between 200 and 850 hPa in AM obtained from (a) NCEP-NCAR reanalysis, and (b) EXP_CLM. The unit is m sec^{-1}.

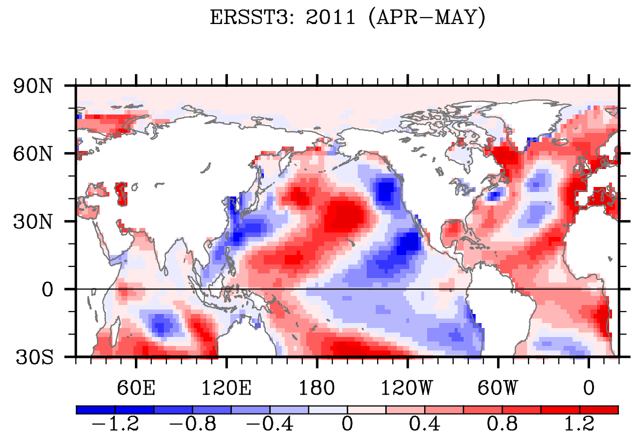

Figure 14. Anomalous SST in AM of 2011 obtained from ERSST3. The unit is °C.

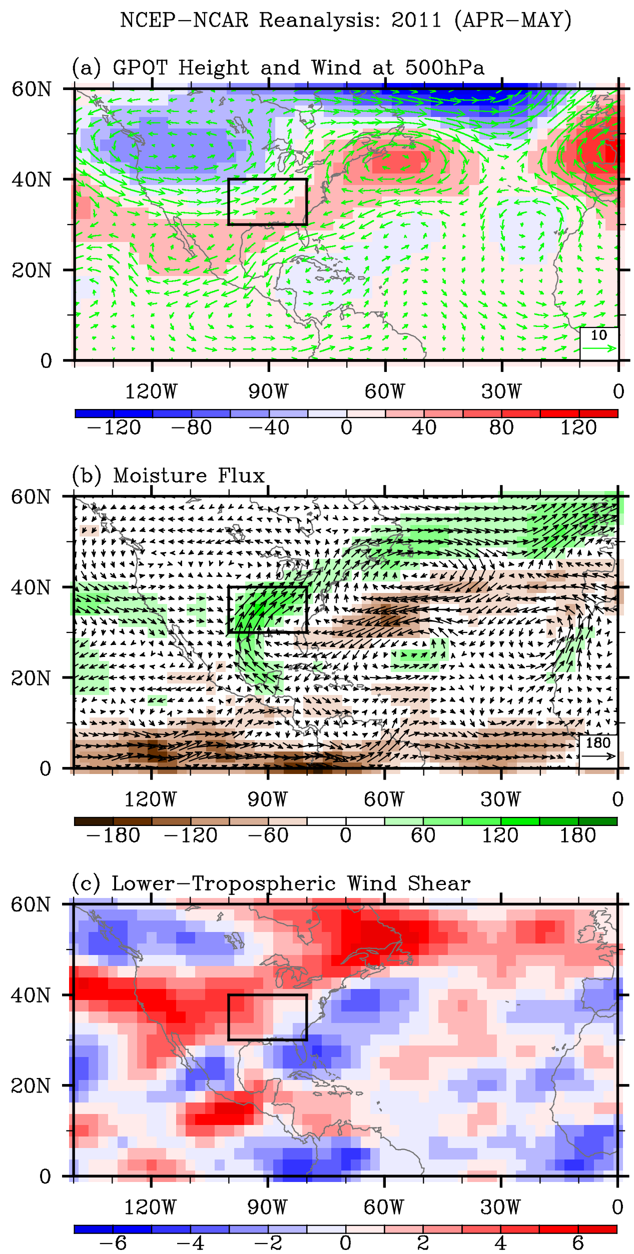

Figure 15. Anomalous (a) geopotential height and wind at 500 hPa, (b) moisture transport and lower-tropospheric (500 hPa – 925 hPa) vertical wind shear in AM of 2011. The moisture transport, geopotential height, wind and wind shear are obtained from NCEP-NCAR reanalysis. The unit is kg m^{-1} sec^{-1} for moisture transport, m for geopotential height, and m s^{-1} for wind and wind shear. The small box in (a), (b) and (c) indicates the central and eastern U.S. region frequently affected by intense tornadoes.

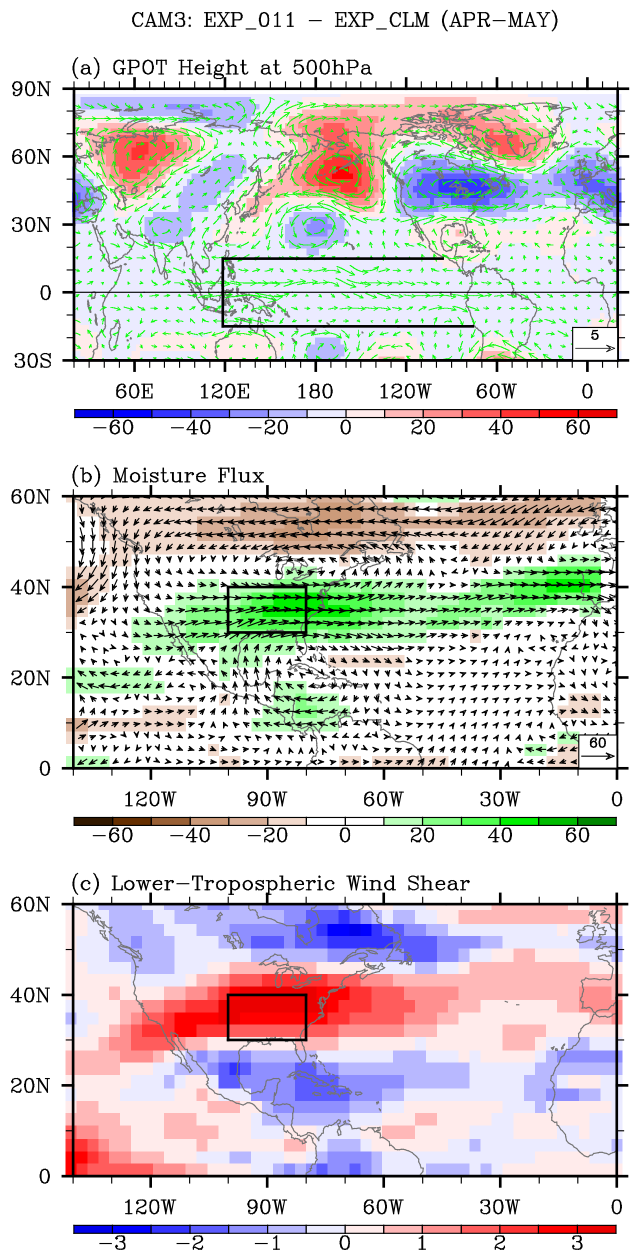

Figure 16. Simulated anomalous (a) geopotential height and wind at 500 hPa, (b) moisture transport and (c) lower-tropospheric (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_011 – EXP_CLM. The unit is kg m^{-1} sec^{-1} for moisture transport, m for geopotential height, m s^{-1} for wind 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. The values of the 90% confidence interval averaged over the North America (30^{o}N-50^{o}N, and 120^{o}W-70^{o}W) are 1.3, 17 and 1.0 for a, b and c, respectively.

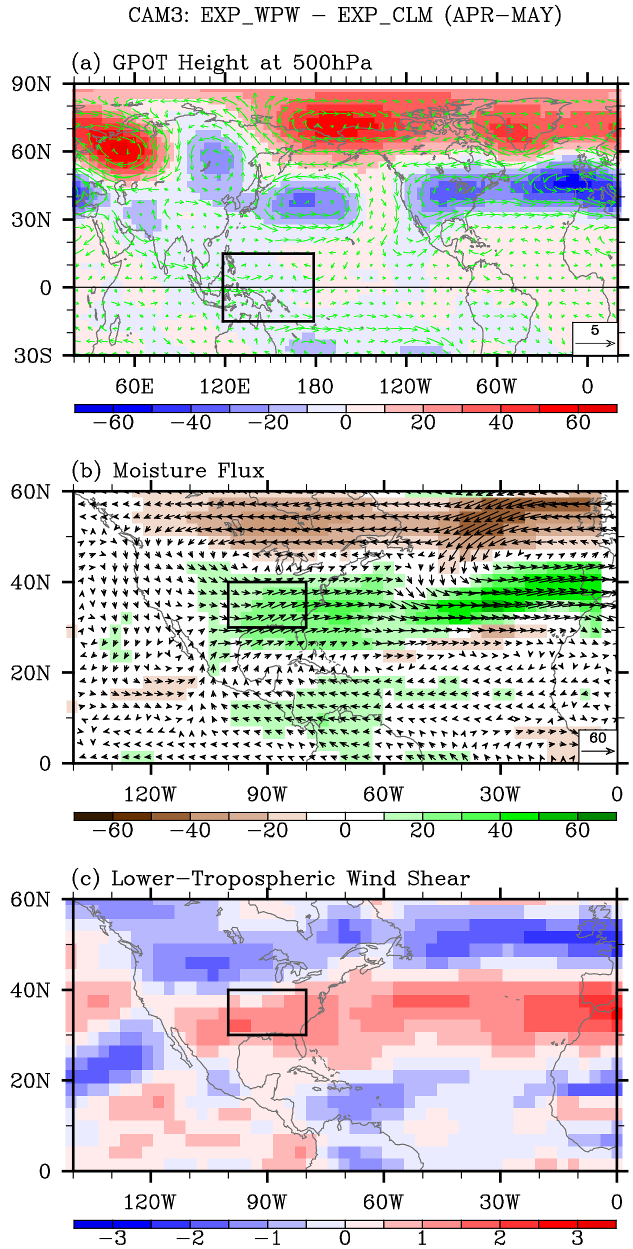

Figure 17. Simulated anomalous (a) geopotential height and wind at 500 hPa, (b) moisture transport and (c) lower-tropospheric (500 hPa – 925 hPa) vertical wind shear in AM obtained from EXP_WPW – EXP_CLM. The unit is kg m^{-1} sec^{-1} for moisture transport, m for geopotential height, m s^{-1} for wind 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. The values of the 90% confidence interval averaged over the North America (30^{o}N-50^{o}N, and 120^{o}W-70^{o}W) are 1.5, 21 and 1.2 for a, b and c, respectively.

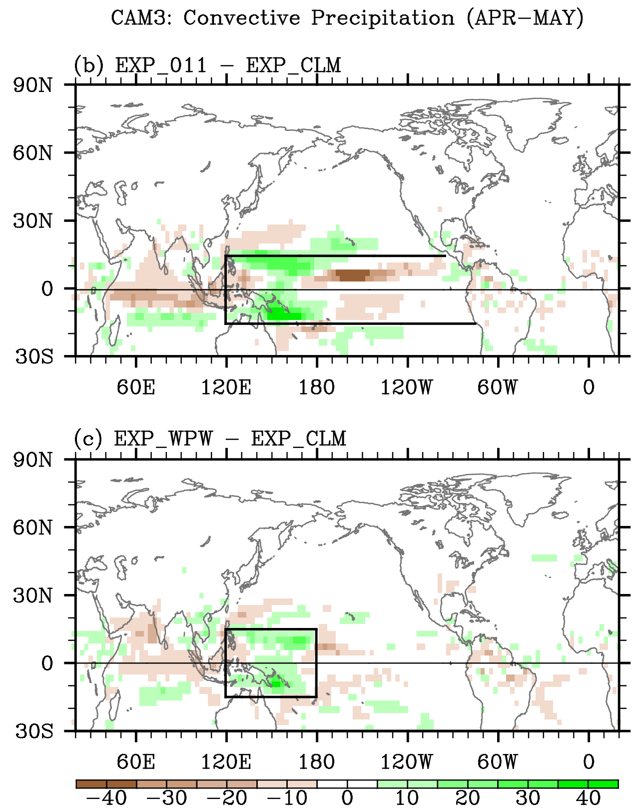

Figure 18. Simulated anomalous convective precipitation rate in AM obtained from (a) EXP_011 – EXP_CLM, and (b) EXP_WPW – EXP_CLM. The unit is mm day^{-1}. Thick black lines in (a) and (b) indicate the tropical Pacific region where the model SSTs are prescribed. The values of the 90% confidence interval averaged over the tropical Pacific (15^{o}S-15^{o}N, and 120^{o}E-coast of the Americas) are 5.8 and 5.3 for a and b, respectively.

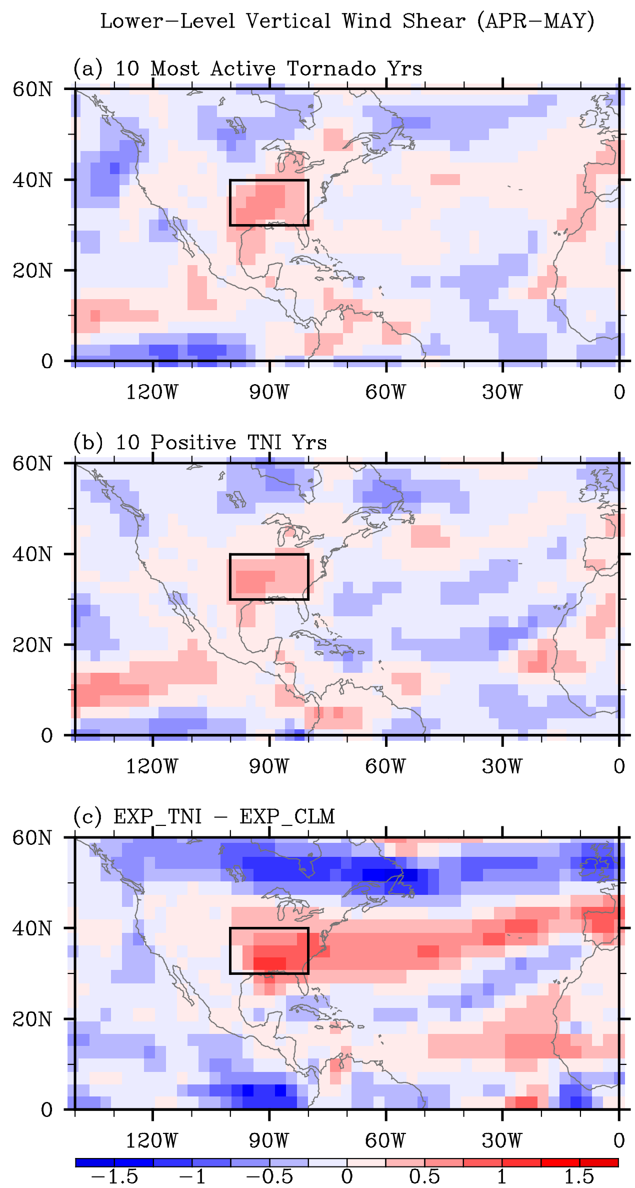

Figure 19. Anomalous lower-level (850 hPa – 1000 hPa) vertical wind shear for (a) the ten most active U.S. tornado years and (b) the top ten positive TNI years in AM during 1950-2010 obtained from NCEP-NCAR reanalysis. (c) Simulated anomalous lower-level (850 hPa – 1000 hPa) vertical wind shear in AM obtained from EXP_TNI – EXP_CLM. The unit is m s^{-1}. The small box in (a) - (c) indicates the central and eastern U.S. region frequently affected by intense tornadoes. The values of the 90% confidence interval averaged over the North America (30^oN-50^oN, and 120^oW-70^oW) are 0.4, 0.4 and 0.3 for a, b and c, respectively.