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

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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 (i.e., from F3 to F5 in the Fujita-Pearson scale) 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 (Verbout et al. 2008). The threshold number selected in this case is three and above, which roughly represents the upper 25% in the number of intense U.S. tornadoes in a given day of AM during 1950-2010. 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). 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). 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 passes over the area.

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 of TNI, 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 thus 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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