Climatic role of North American low-level jets on U.S. regional tornado activity

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Abstract

Regional connectivity of North American low-level jets (NALLJ) to springtime tornadic activity is analyzed in reanalysis data and the SPC severe weather database. Extraction of preferred modes of NALLJ variability for 1950-2010 are used to identify three regions over the U.S. based on regional footprints of NALLJ activity. Connectivity of the regional NALLJ modes and tornadic activity to SST variations indicate that the structure of SST linkages are highly dependent on the selected region and multidecadal epoch, which is highlighted by regional NALLJ and tornado indices showing SST variability patterns similar to the PDO for northern Great Plains tornadoes and NALLJ Mode 1, and the Trans Nino pattern (warm east cold central Pacific) for southeast tornadoes and NALLJ Mode 2. All SST regressions are stronger in the more recent decades (1979-2010) when compared to the full 1950-2010 time period.

The influence of NALLJ variability on the tornadic environment is also assessed and shows interesting regional spatial patterns in anomalies of convective available potential energy (CAPE), helicity (HLCY), and the lifted index (LI). This regional environmental parameter analysis demonstrates the complexity of the NALLJ influence on specific tornado regions and partially explains that, although each NALLJ mode is primarily connected to a specific region, there are regional overlaps to be considered.

1. Introduction

The need for increased understanding of regional climate variability and change has recently been elevated within the national and international climate science communities. Among the many facets of this framework is the further refinement and characterization of the linkage between extremes of weather and climate. Indeed, the societal impacts of climate variability and change are typically communicated through the weather timescale. As such, placing extreme weather phenomena in a climate context can further our scientific understanding of the characteristics of the weather-climate linkage.

Recent tornado outbreaks over the U.S. have caused devastating societal impacts with significant loss of life and property. Fortunately, the Storm Prediction Center (SPC) provided adequate warnings days in advance of the major tornado outbreak episodes during the spring of 2011, which undoubtedly saved lives. Nevertheless, the recent call for increased understanding, attribution, and prediction of tornadic activity on seasonal timescales necessitates an examination of potential climate factors that influence the seasonal variability of the tornadic environment.

To some extent the seasonal climate variability over North America is linked with phases of the El Niño Southern Oscillation (ENSO) (Ropelewski and Halpert 1987). Variations in the location of tropical heating anomalies associated with ENSO modulate the general circulation over the United States, providing the background environment for climatic anomalies. This linkage is strongest during the boreal winter; however, the atmospheric response may be delayed by 1-3 months, lingering well into the following spring (Kumar and Hoerling 2001). Recent studies have investigated the ENSO linkages of annual U.S. tornadic activity to traditional ENSO indices (Marzaban and Schaeffer 2001), and wintertime tornado outbreaks (Cook and Schaefer 2008). These studies characterized the correlation between ENSO and U.S tornadoes as weak, although statistically significant. Modeling experiments have supported the weak connectivity between distinct ENSO phases and tornadoes in general, however, they have indicated that a positive Trans-Niño index (TNI) (i.e., warm east Pacific cool central Pacific) is more strongly linked to increased tornado activity over the U.S. in spring, than the traditional ENSO indicators (Lee et al. 2011).

While results are inconclusive, there is some indication that boundary forced climate variability (ENSO and its transitions, perhaps others) contributes to U.S. tornado activity, and that it is not purely a result of atmospheric internal variability. Nevertheless, the regional climate mechanisms that more directly force variability in seasonal tornadic activity, and their relationship to large scale climate variability, remain to be fully elucidated. Indeed, many factors are necessary for supporting the dynamic and thermodynamic environment conducive to the formation of tornadoes. In general it is required that high levels of atmospheric instability are present, however, it is also vital that dynamic processes are present to both support the highly unstable thermodynamic environment (Brooks et al 2003), and provide the necessary mechanical triggering mechanism for the maintenance of seasonal tornadic activity. One such feature of the springtime circulation are North American low-level jets (NALLJ), which have long been recognized as the primary mechanism for generating and focusing extreme flood events on weather and climate timescales through moisture transports, their convergences, and enhancing atmospheric instability, most notably over the Great Plains (Weaver, Ruiz-Barradas, and Nigam 2009).

In this analysis we investigate the regional springtime April, May, and June (AMJ) NALLJ activity, its relationship to seasonal anomalies of tornado counts over the U.S., and the remote sea surface temperature (SST) linkage. In addition to these spring months being at the heart of the North American tornado season, the motivation is further clarified in Figure 1 which shows the 1950-2010 seasonal evolution of the U.S. climatological tornado counts (red) from the SPC severe weather database (Schaeffer and Edwards 1999) and 850 hPa meridional wind (blue) averaged over the eastern two-thirds of the U.S., as diagnosed from the NCEP/NCAR reanalysis (Kalnay et al 1996). Tornado counts and the southerly low-level meridional wind field show similar evolution throughout the spring with each decaying thereafter, although tornado counts decay much more rapidly through the summer months. Additional motivation derives from the idea that, while a great data resource, there is the potential for inhomogeneity in the SPC tornado database due to population shifts and multiple procedural reporting changes over the history of the database (Doswell 2009). Investigating climatic linkages to the tornadic environment, i.e., NALLJ variability and its regional climate impacts, from consistent NCEP/NCAR and CFSR reanalysis data is useful in clarifying the physical basis for seasonal tornado variability in light of possible artificial trends in the tornado database (Brooks 2003).

The data sources and methodology will be described in section 2. NALLJ variability and its regional impact on tornadic activity will be discussed in section 3. Section 4 documents the regional impact of NALLJs on thermodynamic parameters conducive to tornado activity. Section 5 will assess the large scale climate context, diagnosed through the connectivity of NALLJs and U.S. tornadic activity to global sea surface temperature (SST) variability, while section 6 is left for the discussion.

2. Data and Methodology

The SPC tornado/severe weather database is used to extract monthly tornado counts over the continental U.S. (CONUS) and a subset of regions (defined in section 3) for the years 1950-

2010. The dataset was subject to a linear detrending to ameliorate the effects of changes in population, tornado assessment practices, National Weather Service Guidelines, and other inhomogeneities. These characteristics are discussed more thoroughly in Brooks (2003) and Doswell (2005). Much of the positive trend in tornadoes is reasoned to be a manifestation of incorrect reporting of F0 tornadoes throughout the record and if these are ignored the trend largely disappears (Brooks, personal communication).

NALLJ variability for the 1950-2010 period is assessed by conducting an EOF analysis on the monthly AMJ 850 hPa meridional wind field over the domain 105-80°W:20-50°N in the NCEP/NCAR reanalysis. As in Weaver and Nigam (2008) a covariance-based analysis on $(\cos\theta)^{1/2}$ weighted field (θ is latitude to insure grid parity) was performed. The EOFs are not rotated given the limited analysis domain. The principal components obtained from this analysis are used in relating NALLJ variability to AMJ seasonal tornadic activity and global SST variations. To assess seasonally averaged AMJ linkages to NALLJ activity each modes PC is averaged across all months to produce the AMJ seasonal mean PC. While more modern reanalyses are available (JRA, MERRA, CFSR) none posses a historical record long enough to temporally align with the SPC tornado database (1950-2010). Furthermore, the representation of the large scale wind fields over the U.S. is quite good in this reanalysis system given the influence of a large number of assimilated observations there (Kalnay et al. 1996).

To investigate the thermodynamic environment important for tornadic activity we apply NALLJ PC regressions/correlations to select parameters from the brand new state-of-the-art Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010). This new reanalysis system takes advantage of significant modeling and data assimilation upgrades developed in the ~ 15 years since the generation of the NCEP/NCAR reanalysis. As such we use it here to assess anomalies of Convective Available Potential Energy (CAPE), 0-3000 meter Helicity (HLCY), and the Lifted Index (LI), which are all important indicators of potential tornadic activity. Despite the truncated (1979-2010) record in the CFSR as compared to the NCEP/NCAR reanalysis, the dependence of these thermodynamic parameters on features of the assimilating model necessitates that we use the latest technological advances in reanalysis for assessing these parameters.

SST links are facilitated by using the Extended Reconstructed Sea Surface Temperature version 3 (ERSSTv3) (Smith et al 2008), while monthly precipitation is from the Precipitation Reconstruction (PREC) described in Chen, et al. (2002).

3. Regional NALLJ and Tornadoes

Given our interest in NALLJ variability and the potential impact on tornado environments we first investigate the mean characteristics of the low-level wind over the continental U.S. as shown by the mean AMJ 850 hPa wind in Figure 2. The climatological Great Plains low-level jet (GPLLJ) is clearly evident by the wind maxima over central Texas with a northward push into the upper Midwest. While weaker, the mean 850 hPa southerly flow extends eastward to the southeast coast of the U.S. generally encompassing much of the eastern two-thirds of the U.S.

a. NALLJ Modes

North American low-level jets are identified by performing an EOF analysis on the monthly AMJ 850 hPa meridional wind field over the domain of 20-50°N and 80-105°W for 1950-2010 from the NCEP/NCAR reanalysis. Shown in Figure 2 are the first three modes of NALLJ variability as diagnosed form the AMJ averaged PC regression to 850 hPa meridional wind (contoured) and precipitation (shaded). Together the first three modes explain ~72% of the regional 850 hPa meridional wind variance with mode 1, mode 2, and mode 3 explaining 41%, 20%, and 11% of the variance respectively.

NALLJ Mode 1 is characterized by significant strengthening and expansion of the climatological Great Plains low-level jet, which is typically active in a narrow band between 95-100°W and 25-35°N (Figure 1). This mode shows a widely distributed precipitation impact with pockets of strong precipitation anomalies spread throughout the central and northern Great Plains, apparently a reflection of the enhanced moisture transport from the Gulf of Mexico[1].

NALLJ Mode 2 shows a double jet structure characterized by opposing regional 850 hPa meridional wind anomalies converging over portions of the Great Plains and upper Midwest. As in Mode 1 there is a deep penetration of tropical moisture, in this case into the southeastern U.S. Gulf States and Mississippi river basin. While the southerly anomalous flow is weaker in Mode 2 as compared to Mode 1 the precipitation and MFC (not shown) impact is actually more substantial on account of the enhanced convergence from the dry northerly low-level jet over the northern Plains.

Mode 3 is substantially weaker than both modes 1 and 2 and has its most significant precipitation impacts over the Southeast U.S. and a small but strong positive precipitation anomaly over the central Plains. The anomalous meridional wind structure of mode 3 shows a triple jet structure with southerly anomalies over the southeast and northern Plains, and a northerly anomaly over the southern Great Plains. In the case of the Great Plains, this mode's anomaly would act to essentially shift the climatological GPLLJ northward and/or eastward.

b. Regional Tornado & NALLJ Variability

[1] This mode has a much more focused NGP precipitation footprint during mid-late summer (i.e., JAS) and was a major instigator of the 1993 Midwest floods (Weaver and Nigam 2011).

The NALLJ patterns (cf Fig. 3) point to three key regions for further analysis, the northern Great Plains (NGP), southern Great Plains (SGP), and Southeast (SE). While the anomalous precipitation patterns do not explicitly identify latitude and longitude boundaries, the precipitation and MFC impact regions are quite similar to those identified by Schaeffer and Edwards (1999). Given the similarities with our impact regions we adopt a similar regional definition as identified in Figure 3 with the NGP 39-49°N:95-105°W, SGP 29-39°N:95-105°W, and SE 30-40°N:80-90°W regions.

Figure 5 shows the Principal Component time series for NALLJ mode 1 (blue circle), mode 2 (green circle), and mode 3 (red circle) and the three regional detrended tornado indices, NGP (blue bar), SE (green bar), and SGP (red bar)[2]. The tornado indices are the time series of AMJ tornado count anomalies formed by subtracting the detrended long term (1950-2010) mean AMJ tornado counts.

Even in detrended tornado data (bars) there appears persistent negative anomalies throughout the early parts of the record (1950-1979) for all 3 regions save 1957, 1965, 1973-74, and 1982. However, since about 1980 there has been increasing interannual variability, and with the exception of the latter half of the 1980's a preference for positive tornado anomalies and increased intra-regional variability (i.e., regions with opposite signed anomalies in the same year). Some historically significant tornado seasons are evident, including 1973-74, and 2003 which are dominated by SE tornado counts, and 1991 and 2008 which were more evenly distributed among the 3 regions. Significant tornado "holes" are also present during the early 1950's and late 1980's.

[2] The NALLJ PCs (circles) are multiplied by a constant scale factor for visual convenience and as such show only relative magnitude.

The PC time series of regional NALLJ activity is also represented in figure 5 by the closed circles. Mode 1 (blue circles) exhibits interannual and decadal variability. The decadal variability is evident by the mostly positive values of this PC during the early years of the period (1950-1978) with more negative values in the latter 1979-2010 period. The PC time series for mode 2 (green circles) shows much stronger interannual variation with no visually discernible decadal component, although there are same-sign groupings of 2-10 consecutive years. Mode 3 (red circles) exhibits much stronger interannual variability as compared to Modes 1 and 2.

From visual inspection it appears that the NALLJ modes and the regional tornado indices may exhibit some degree of temporal association. This makes some physical sense given that there is a regional preference for the 3 NALLJ modes as identified in their precipitation impact. Table 1 displays the temporal correlation coefficients between the 3 NALLJ PCs and the 3 tornado regions (cf. Figure 4) for 1950-2010 and 1979-2010 (parentheses). The correlations have some interesting features, most notably the much stronger correlation of NALLJ PC 1 with both the NGP and SGP tornado indices in the 1979-2010 period as compared to 1950-2010. In fact the correlation between NALLJ PC 1 and the SGP has nearly doubled! NALLJ PC 2 has some degree of connectivity to all 3 regions, however the connection to the SE is the most prominent and unlike in PC 1, is stable with respect to the two target time periods. NALLJ PC 3 has weak correlations to the SE and NGP and only appears to be important for the SGP tornado regions for 1950-2010 and is significantly weaker in the more recent period.

4. Tornadic Environment

The variations in NALLJ connectivity to regional tornadic activity bring to the forefront some intriguing questions, including: How does NALLJ Mode 1 influence both the NGP and

SGP especially during the more recent 1979-2010 period? Especially when the NGP shows a more robust positive precipitation footprint in association with NALLJ PC 1 over the more recent decades, largely coincident with the low-level MFC at its exit region (see Weaver and Nigam 2008 Figure 12). Why and how does NALLJ Mode 2 contribute to seasonal tornadic activity over all 3 regions? Finally, why is Mode 3 so weakly correlated to all three tornado regions, despite its strong precipitation impacts, deep tropical moisture fetch, and PC amplitude that is comparable to Mode 2 [3].

To investigate these questions Figure 5 shows NALLJ PC regressions to three environmental parameters that are traditionally linked to tornado activity. Seasonal AMJ anomalies of Convective Available Potential Energy (CAPE), Helicity (HLCY), and the Lifted Index (LI) were regressed against the three NALLJ PCs. These three thermodynamic parameters are provided by the CFSR for 1979-2010. Positive (negative) anomalies of CAPE (LI) indicate enhanced atmospheric instability, while positive HLCY values indicate increased level of atmospheric shear, a necessary requirement for tornadic activity.

Mode 1 shows strong anomalies of CAPE from the Gulf Coast of Texas through the SGP and into the NGP with the largest CAPE values to the east of the axis (red line) of this NALLJ mode. The strongest HLCY is positioned to the west of the jet axis and has high values in both the southern and northern Great Plains, although the extent of the largest values is in the NGP. The lifted index regressions show positively buoyant air over much of the eastern two-thirds of the U.S. with maxima collocated with the highest CAPE values.

The structure for Mode 2 exhibit substantial differences from those in Mode 1. Although the CAPE maxima in the SE corner of the NGP box is still evident, there is a sharp gradient of

[3] This implies that if PC 3 was used for reconstructions, the meridional wind and precipitation (or any other regressed parameter) amplitude would be comparable to Mode 2 which has strong SE tornado correlations.

CAPE anomalies bisecting the northern and southern Great Plains on account of the eastward shift of the entire spatial pattern and the presence of the northerly NALLJ, which would inject drier and more stable air to the NGP, however also enhancing the low-level convergence. Additionally, anomalous CAPE values associated with Mode 2 are weaker in all regions, and especially the SE. The HLCY pattern is much stronger in Mode 2 than in either Mode 1 or 3 and although the maxima is centered in the SGP box there are substantial anomalies throughout the SE region, not surprising given the rotational effects induced by converging air from opposing directions in this mode. The lifted index regressions show weaker anomalies over the SE region, although evidently the combination of high CAPE and Helicity (and perhaps other factors) are sufficient to overcome the weaker LI anomalies. While the strongest correlations between NALLJ PC 2 and the three tornado regions occur over the SE there is also some connectivity to the NGP and SGP, albeit weaker, potentially the result of strong gradients of CAPE and HLCY over the NGP and SGP.

Recall that initially it was somewhat surprising that NALLJ Mode 3 demonstrated such low correlations to all 3 tornado regions (table 1), especially in the 1979-2010 period. However, upon inspection of the tornadic parameters regressed against NALLJ PC 3 it is clear why this mode does not influence the tornadic environment. Weak anomalies in all three fields are evident, and although there is a comparable amount of CAPE and LI with respect to the mode 2 regressions, there are negative HLCY anomalies, a situation that is detrimental to the tornadic environment.

5. Remote Influences

Since SST anomalies have the potential to provide attribution and prediction capability on seasonal timescales it is important to assess the relationships of the NALLJ and tornado activity to the seasonal SST variability. The linkage between global SST variability and the GPLLJ has been recently investigated in observations and model simulations (Weaver et al. 2009). However, much of that study was Great Plains centric and did not specifically take into account the presence of distinct modes of LLJ variability over greater North America, as is done here. Connectivity of tornadic activity to ENSO indices has proved inconclusive with varying degrees of results, most of which demonstrate a weak linkage. While some of these studies did take into account the regionality of tornadoes and their linkage to traditional ENSO indices (Marzaban and Schaefer 2001), or provide a general description of regionality based on ENSO and annual tornado activity (Cook and Schaeffer 2008), here we compare the spatial pattern of global SST variability to all 3 of the regional tornadic indices, and the NALLJ PCs for Modes 1 and 2 during AMJ, the peak of the tornado season [4].

a. Great Plains

Figure 7 shows the NGP tornado (left) and NALLJ PC1 (right) index regressions to SST variability over much of the global oceans for 1950-2010 (top) and 1979-2010 (middle). Each of the four separate indices (i.e., NALLJ and tornado) shows the same general SST pattern over much of the global oceans, although the NGP tornado index shows much stronger amplitude during the more recent period. While all 4 SST patterns show some degree of similarity in the north Pacific, it's interesting that over the 1950-2010 period the tropical Pacific SST patterns representing NALLJ PC1 and NGP tornadoes are oppositely signed and that in the recent 1979-2010 period the ENSO region influence is weaker. Nevertheless, the overall agreement in global SST patterns between the NGP tornado and NALLJ PC1 is quite good in the recent period. The difference in tropical SST patterns between NALLJ PC1 and the NGP tornado index is not

[4] Given NALLJ PC3 unremarkable connection to any of the three tornado regions as identified by very weak environmental parameters we do not analyze the potential SST influence on this Mode.

necessarily surprising given that the correlation of NALLJ PC1 and NGP tornadoes is only 0.35 over the 1950-2010 period.

Recalling that in the recent period (1979-2010) the correlation of NALLJ PC1 and the SGP tornado index is much stronger (0.57) than in the 1950-2010 record, Figure 7 (lower panels) shows regression of SST anomalies against the SGP tornado index for 1950-2010 (lower left) and 1979-2010 (lower right). While some similarity to the Pacific decadal variability in the north Pacific is possible, it is weaker in the 1950-2010 period, which shows a traditional ENSO footprint. Perhaps more importantly, both time periods show a distinct connection to the Niño 3.4 region, although in the recent period the maximum in SST appears strongly over the central Pacific as opposed to spanning the entire tropical east Pacific basin, perhaps a manifestation of the preference for Modoki type El Niño's over recent decades (Yeh et al 2009). All six SST patterns in Figure 7 show warm anomalies over the Gulf of Mexico, an influence that may be important for regional atmospheric stability given the Gulf's role as a reservoir of moisture.

b. Southeast

NALLJ mode 2 is most strongly connected to the SE region, as evidenced by the environmental parameters (Figure 6) and the temporal stability of the correlation between PC2 and the SE tornado index (Table 1). Figure 8 shows the SE tornado (left) and NALLJ PC2 (right) index regressions to SST variability over much of the global oceans for 1950-2010 (top) and 1979-2010 (lower). There are distinct differences as a function of both index and period choice. While all four regression patterns show some degree of cooling in the central tropical Pacific, it is stronger in the recent 1979-2010 period for both NALLJ PC2 and the SE tornado index. One striking feature when comparing the NALLJ PC2 and SE tornado indices is the strong warm eastern tropical Pacific in the NALLJ mode 2 SST regression as compared to the SE tornadic activity, which depicts a neutral and cold eastern tropical Pacific SST for the 1950-2010 and 1979-2010 periods respectively.

c. Discussion

From the analysis of the SST regressions to regional tornadic NALLJ variability it is a bit more clear why previous studies have showed such weak connectivity to the ENSO. Indeed the SST regression values for the three tornado regions are weak, however, it is quite possible to have regional tornado seasons approaching +- 3 and even 4 standard deviations, which in the case of the SGP SST regressions would indicate a > 0.5°C SST anomaly over the tropical Pacific in a strong SGP tornado year. For the SE region there is significantly weaker connectivity to tropical SST over the core ENSO region, and even a strong tornado year may not produce a contribution from tropical Pacific SST above the traditional 0.5°C threshold. Still, this does not necessarily indicate the absence of a roll for tropical Pacific SST in regional tornadic activity, especially given the transitional nature of ENSO during the boreal warm season.

Furthermore, seasonal tornadic activity is dependent on a myriad of dynamical and thermodynamical factors coming together in symbiotic alignment, of which SST variability is only one component. Illustrating this point are the NALLJ PC regressions to SST. While some general features of the tropical SST patterns are shared with their regional tornadic counterparts, the NALLJ modes exhibit much stronger regression patterns. This is expected given that these are distinct modes of variability and as such are orthogonal to each other, which is not the case in the regional tornado data. Using distinct NALLJ Modes may be a cleaner indicator of the link between SST and the tornadic environment, and may be especially useful in light of the temporal consistence concerns surrounding the tornado data.

Despite the fact that the prediction and attribution of seasonal climate variability is inextricably linked to ENSO, there are indications here that the seasonal NALLJ (and to some extent tornadic activity) may be influenced by decadal modes of variability. This is especially apparent in the NGP and NALLJ PC 1 case during the recent 1979-2010 period (Figure 7) as seen in both the north Pacific and north Atlantic. The NGP and NALLJ PC 1 SST regression patterns show a strong tongue of positive SST anomalies stretching across the mid-latitude Pacific with an oppositely signed cold tongue emanating from the southwest coast of North America into the central Pacific, much like the canonical PDO pattern (Mantua 1997). The tornado regressions also show a positive horse-shoe like pattern in the Atlantic reminiscent of the AMO (Enfield et al 2001), however weaker in the NALLJ PC 1 case and given the tornado index analysis strategy (i.e., regressions) it is not clear to what extent this may actually be a lagged influence from the Pacific.

The east/west dipole in SST regressions over the tropical Pacific in NALLJ PC 2 indicates that using the traditional ENSO indices will most likely yield mixed results, i.e., a negative Niño 4 and positive Niño 3 amplitude. Recent observational and modeling evidence suggests that a positive value of the Trans Niño Index (TNI), defined as the difference in Niño 1+2 and Niño 4 regions, is significantly correlated with springtime U.S. tornadic activity (Lee et al 2011). This is consistent with the strong regressed SST gradient from NALLJ PC 2, especially over the recent period. The regressed TNI value for this PC is 0.37K (0.51K) for 1950-2010 and (1979-2010).

6. Summary and Conclusions

Characteristics of springtime tornadic activity over the U.S. are assessed from the perspective of regional tornado indices and distinct modes of NALLJ variability. The assessment is important for understanding the role that NALLJs have in seasonal tornadic activity as NALLJs are an extremely important driver of warm season climatic anomalies and extreme events over the U.S. The selection of tornadic regions is facilitated by analyzing the precipitation impacts of the various NALLJ modes. Seasonal tornado and NALLJ activity is further framed in a large scale climate context by assessing their connectivity to global SST patterns. This is especially important given the inconclusiveness of recent studies regarding the correlation of tornadic activity to ENSO, and the potential inhomegeneities in the historical tornado database, a limitation which is much less prevalent in the large scale meridional wind field from consistent reanalysis systems.

The correlation of the selected regional tornado index anomalies and the NALLJ PC's demonstrate the robustness of the NALLJ and regional tornado linkage. NALLJ Mode 1 shows the strongest connection to both the northern and southern Great Plains, with both regions exhibiting a significantly higher correlation over the recent decades, and in the case of the SGP nearly double! It is not clear as to the specific cause of this large correlation increase, however, in the NALLJ Mode 1 we speculate that it is likely a manifestation of natural multi-decadal variability as opposed to a trend, given the obvious multi-decadal nature of the PC 1 time series. Further limiting our ability to assess the veracity of any potential trend from the tornado index perspective are the consistency issues with the tornado data, which bring any trends into question, although it should be noted that for assessing natural variability this dataset is deemed sufficient (Brooks, personal communication). Comparisons of the regressed SST anomalies to the NGP tornado index and NALLJ PC 1 show many similarities, most strongly (weakly) in the PDO (ENSO) region of the Pacific, highlighting the potential influence of multi-decadal variability on the GPLLJ and NGP tornadoes during AMJ.

NALLJ Mode 2 is most strongly connected to the Southeast tornado index and exhibits the strongest correlation of any combination of NALLJ modes and tornado regions over the 1950-2010 period. This mode also has some connectivity to the Great Plains regions. The PC 2 time series shows no significant change in correlations between the 1950-2010 and 1979-2010 periods, unlike PC 1. The SST regressions of the SE tornado index and NALLJ PC 2 are to a large extent similar with the exception of the extreme eastern tropical Pacific in the 1979-2010 time period. More interesting is the potential role of ENSO transitions as diagnosed via the TNI in connection with SE tornadoes and NALLJ Mode 2. Given the warm (cold) east (central) Pacific, investigating a connection to distinct ENSO regions would likely be inconclusive, however not so in the case of the TNI. Furthermore, recent observational and modeling evidence show significant linkages of the TNI to both U.S. tornadoes and enhanced low-level meridional flow, similar to that from NALLJ Mode 2.

While there is a preference for NALLJ variability to influence seasonal tornadic activity over certain regions, there is not a clear separation among the NALLJ modes' impact on regional tornado activity. For instance, although Mode 2 is connected most strongly to the SE it also has some impact (although weaker) on both the NGP and SGP regions. This highlights the fact that numerous regional environmental processes (i.e., CAPE, HLCY, LI, to name a few) need to come together to maintain seasonal tornadic activity, and that despite the regionality of the NALLJ modes, the impact that a particular mode can have on environmental parameters in an adjacent region is sufficient to influence the seasonal tornadic activity outside of the prime NALLJ region. This speaks to the inherent challenges in clarifying the regional climatic differences as it pertains to tornadoes.

Despite these difficulties it is significant that using a single atmospheric parameter, in this case 850 hPa meridional wind, demonstrates such strong connectivity to both regional tornadic activity and global scale SST variations. This potentially has positive implications for developing seasonal prediction methodologies using global climate models, given the large data volumes typically associated with such endeavors. Distilling the regional characteristics of tornadic activity to few essential variables may also facilitate prediction on the intraseasonal timescale (i.e, weeks 1-4) should similar strong connectivity be elucidated. Research on the tornado and NALLJ variability on subseasonal timescale is currently underway in an effort to further our understanding of the tornado NALLJ linkage.

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Tables

	PC1	PC2	PC3
SE	-0.02 (0.03)	**0.50 (0.47)**	0.05 (-0.15)
NGP	**0.35 (0.49)**	**0.24 (0.28)**	0.17 (0.03)
SGP	**0.30 (0.57)**	**0.24** (0.25)	**0.29** (0.13)

Table 1. Correlations of the regional tornado indices and the PC time series of NALLJ Modes 1-3 for 1950-2010 and (1979-2010).

Figures

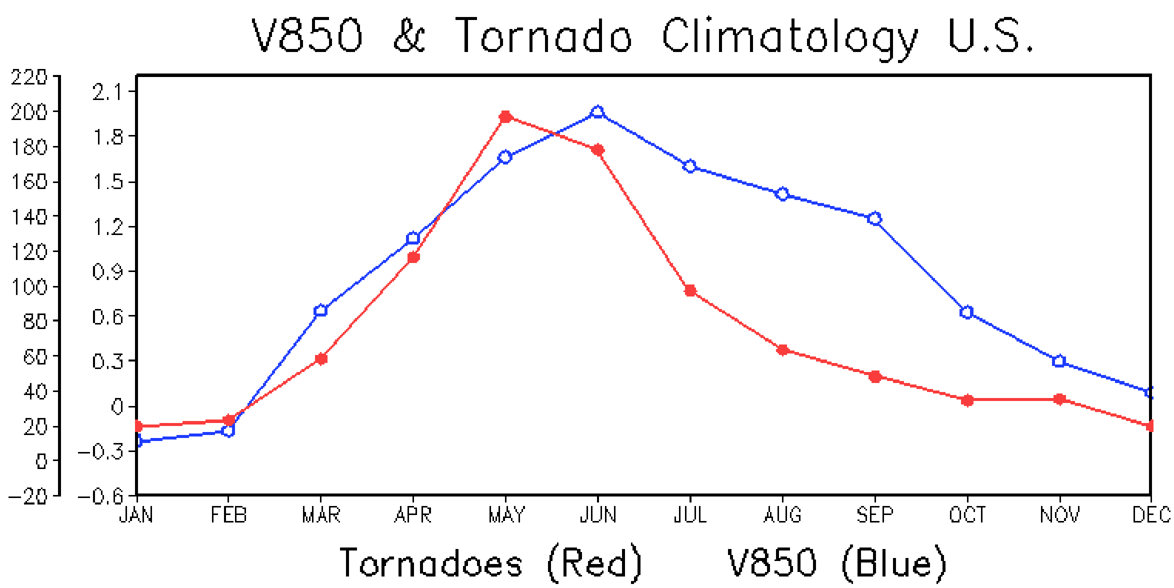

Figure 1. Monthly climatological evolution of the area averaged 20-50°N 105-80°W 850 hPa meridional wind (blue) and all U.S. tornado counts (red) for 1950-2010. The 850 hPa meridional wind is in m s^{-1} and the tornadoes are in raw integer counts.

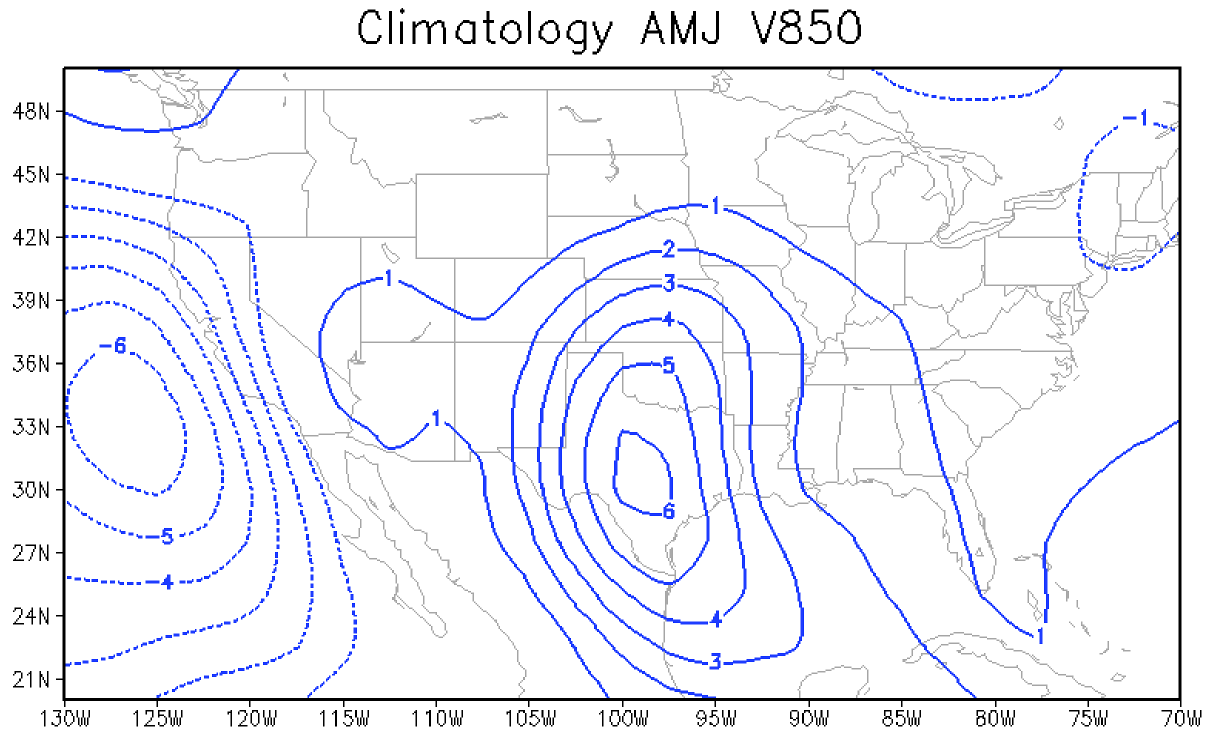

Figure 2. Seasonal mean (AMJ) climatology of 850 hPa meridional wind from the NCEP/NCAR reanalysis for 1950-2010. 850 hPa meridional wind is contoured at 1 m s^{-1}.

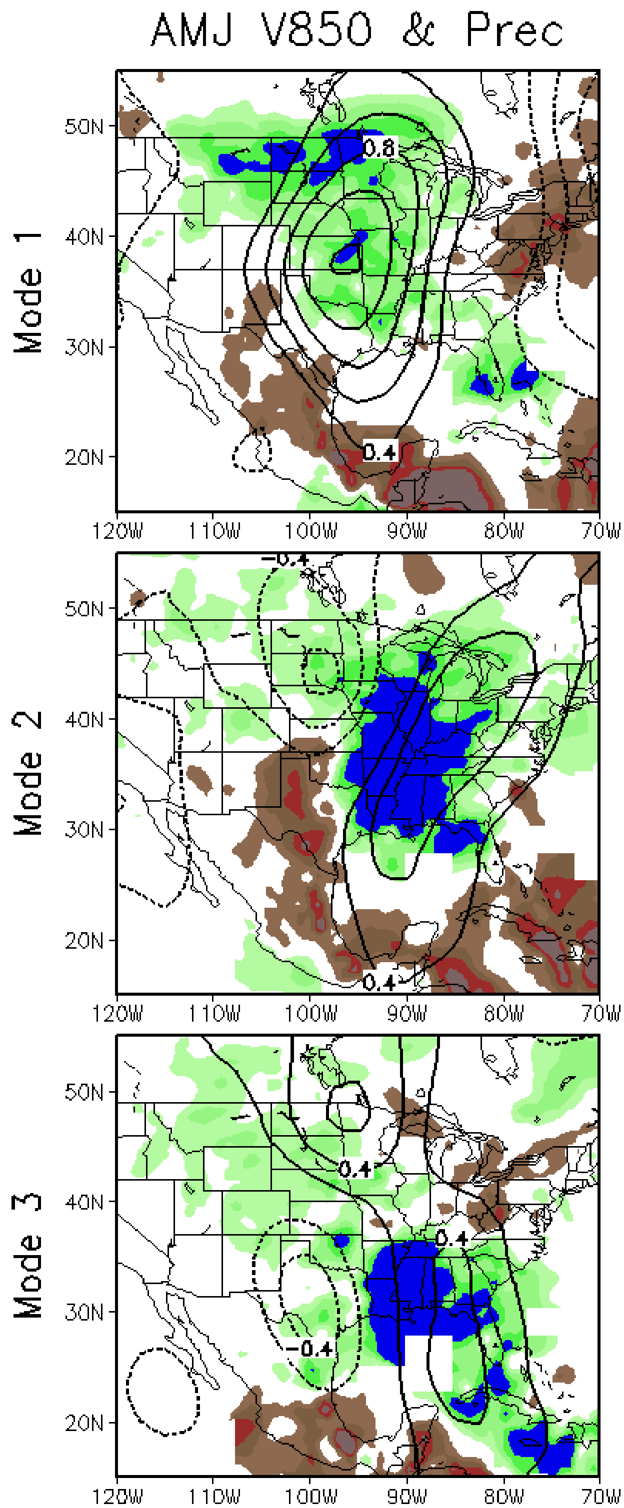

Figure 3. Recurrent patterns of AMJ NALLJ variability (contours) and regressed precipitation (shaded). The EOF modes are contoured at 0.2 m s^{-1} and precipitation is shaded at 0.3 mm d^{-1}.

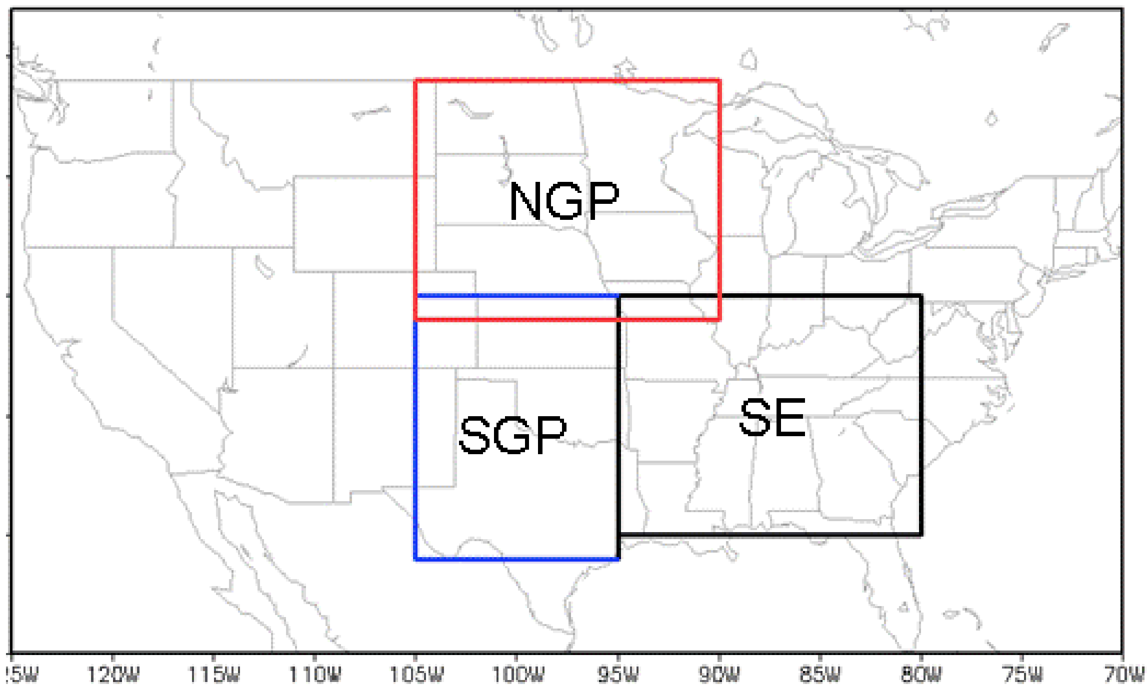

Figure 4. Areas defining the three regional tornado indices: Southern Great Plains (SGP), Northern Great Plains (NGP), and Southeast (SE).

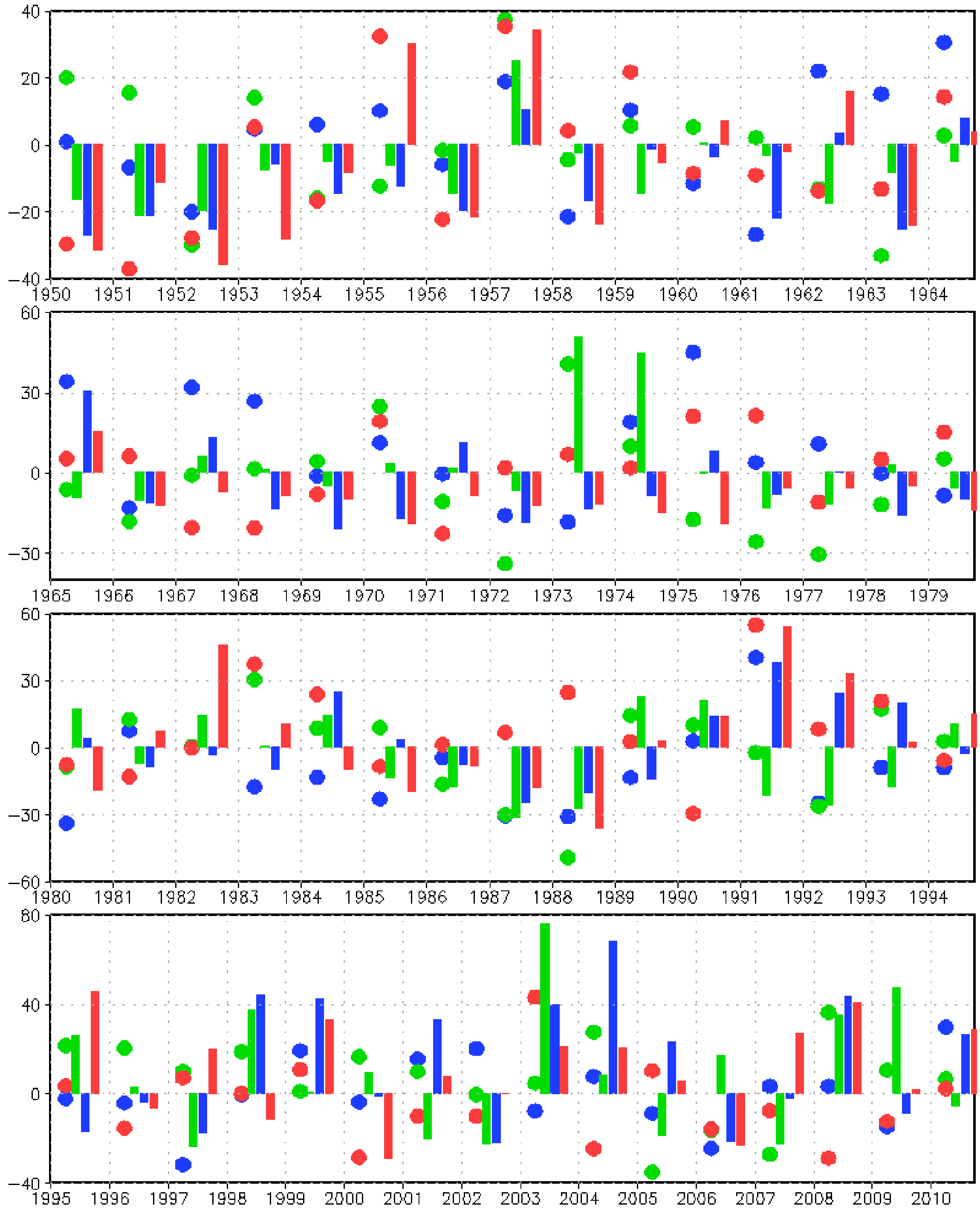

Figure 5. AMJ Regional tornado index anomalies (bars) for the SGP (red), NGP, (blue), and SE (green) for 1950-2010. PC index anomalies (circles) for NALLJ Mode 1 (blue), Mode 2 (green), and Mode 3 (red). The NALLJ PC time series are multiplied by a constant scale factor (30) to facilitate visual comparison.

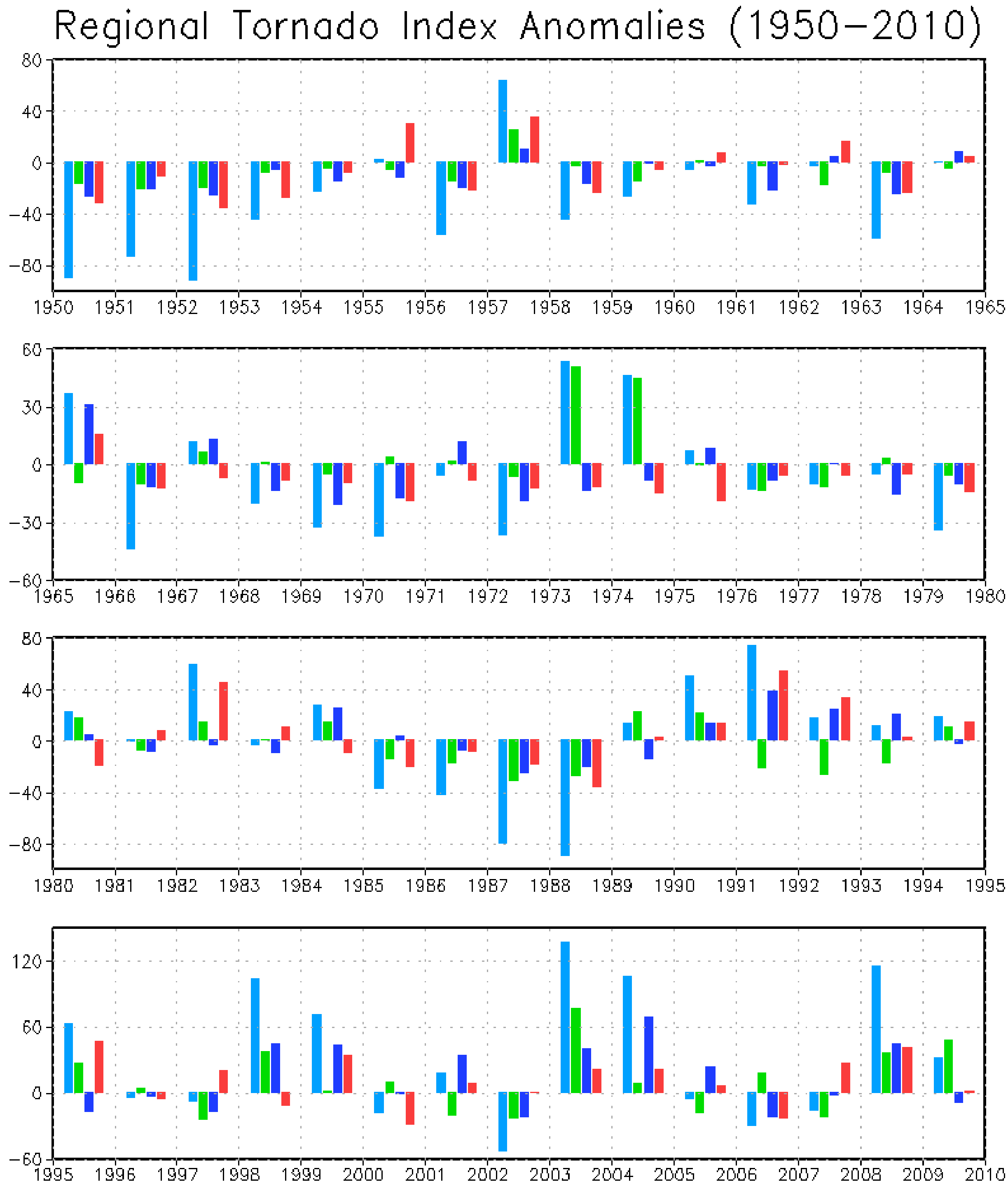

Figure 5a. Potential alternative to Figure 5. AMJ Tornado index anomalies for the CONUS (cyan), SE (green), NGP (blue), and SGP (red) for 1950-2010.

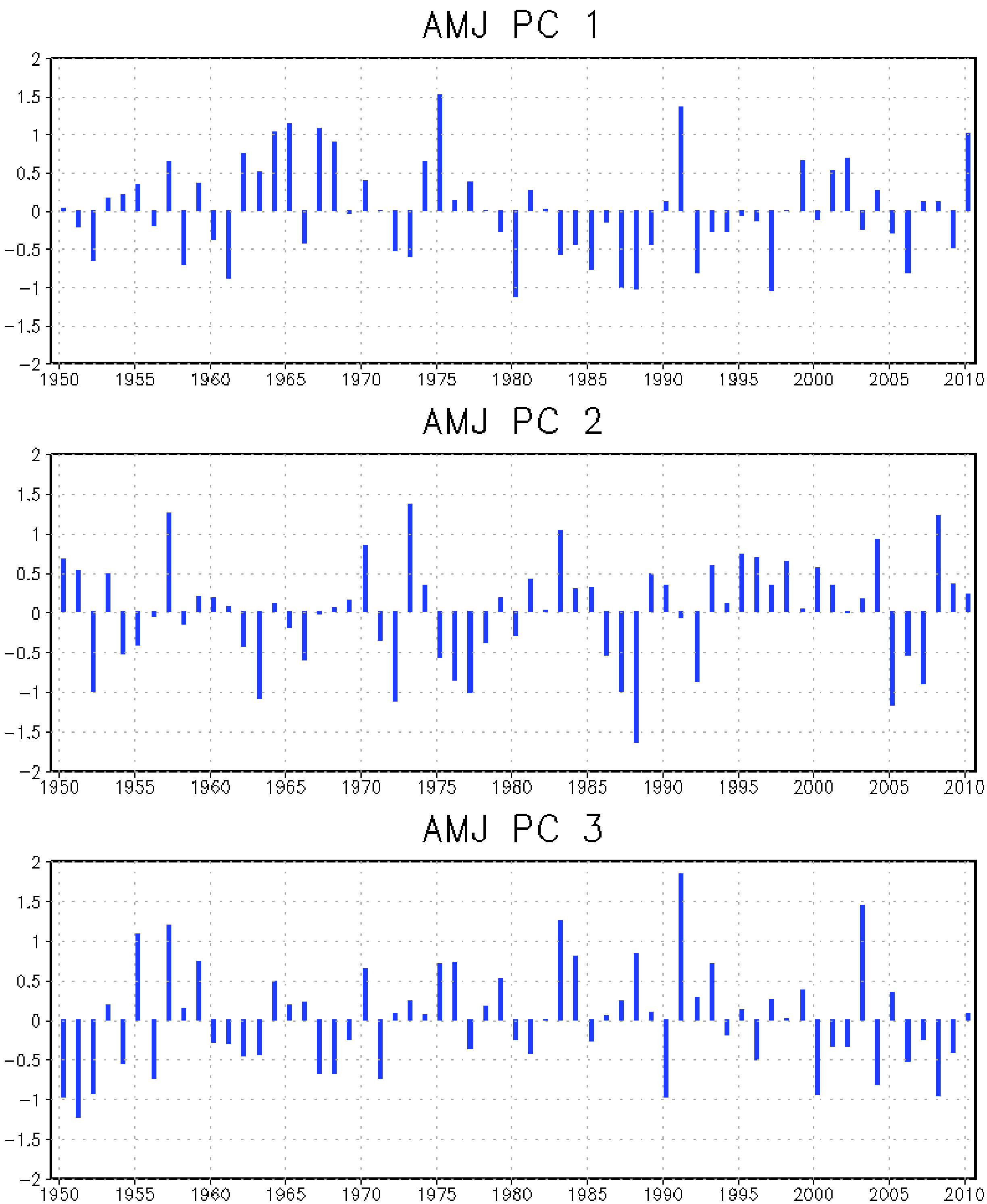

Figure 5b. Potential alternative to Figure 5. AMJ PC index anomalies for NALLJ Mode 1 (top), Mode 2 (middle), and Mode 3 (lower) for 1950-2010.

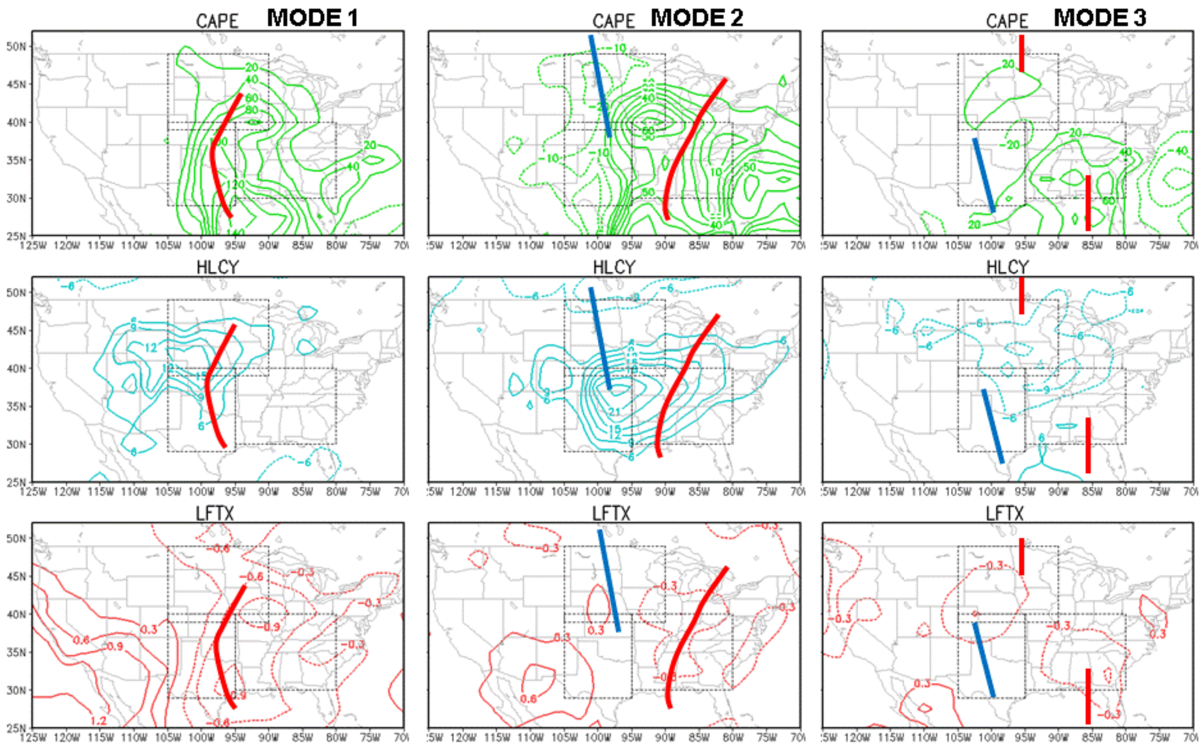

Figure 6. NALLJ PC time series regressions to CAPE (upper), helicity (middle), and lifted index (lower) for Mode 1 (left), Mode 2 (middle), Mode 3 (right) for 1979-2010. Red (blue) solid lines denote the southerly (northerly) jet axes of the indicated mode. Cape is contoured at 20 J/KG, HLCY at 3 m^2/s^2, and LI at 0.3.

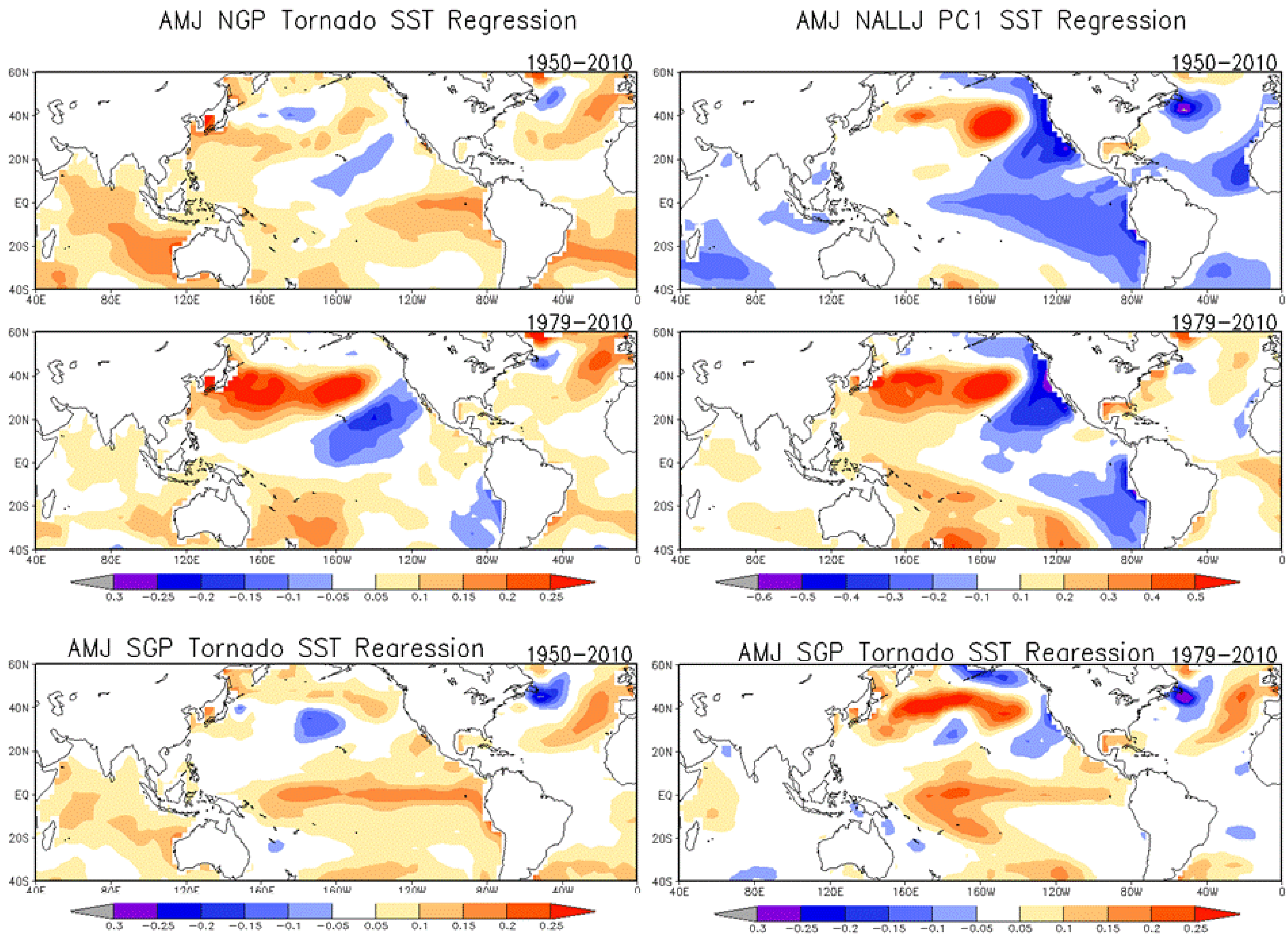

Figure 7. (left) NGP tornado index and (right) NALLC PC 1 regressions to SST for 1950-2010 (upper) and 1979-2010 (middle) for AMJ. (bottom) SGP tornado index regressions to SST for 1950-2010 (left) and 1979-2010 (right) for AMJ. Tornado index regressions are shaded at 0.05 K while NALLJ PC index regression is shaded at 0.1 K.

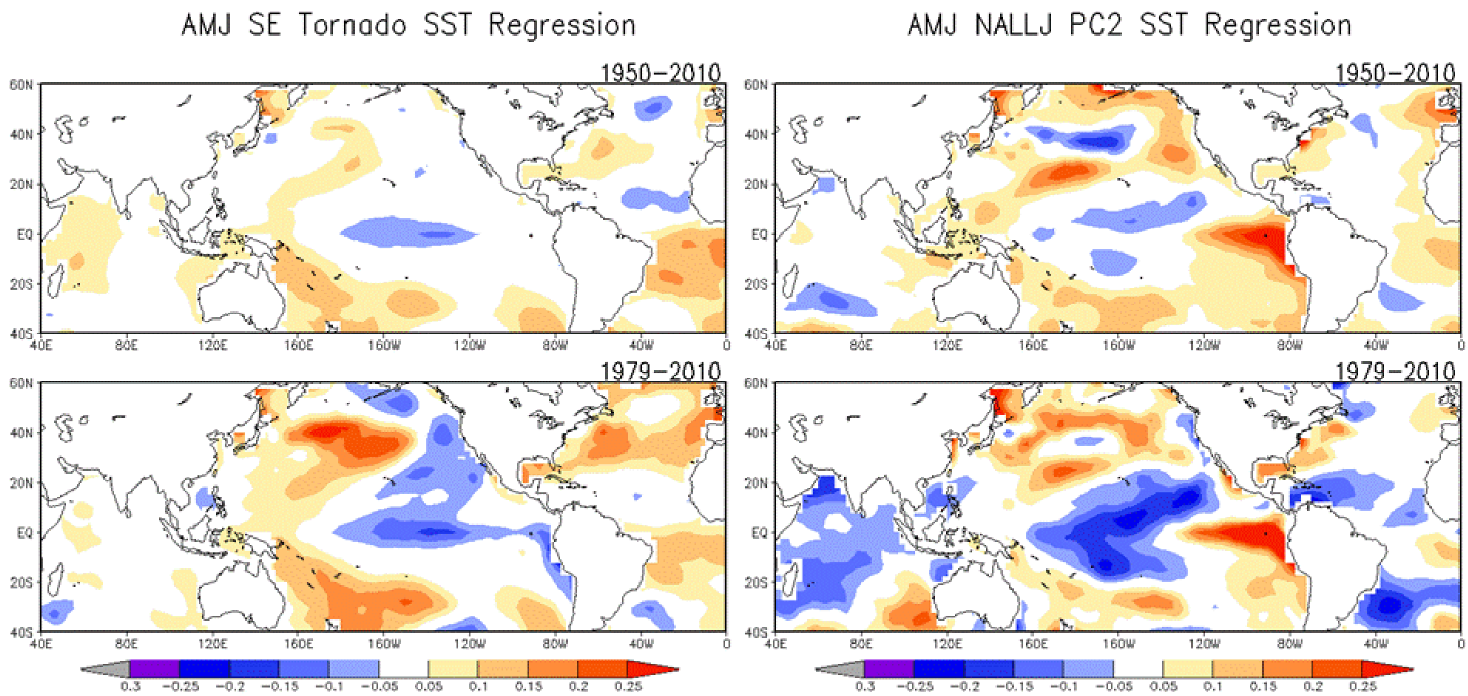

Figure 8. (left) SE tornado index and (right) NALLC PC 2 regressions to SST for 1950-2010 (upper) and 1979-2010 (lower) for AMJ. Tornado index and NALLJ PC 2 regressions are shaded at 0.05 K.