ENSO phase transition in spring and its potential impact on tornado outbreaks in the U.S

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Outline

- Motivation and Background
- Trans-Niño and U.S. Tornado Activity
- Model Experiments
- Summary

CLIVAR - ENSO Diversity Workshop, Feb-7 2013

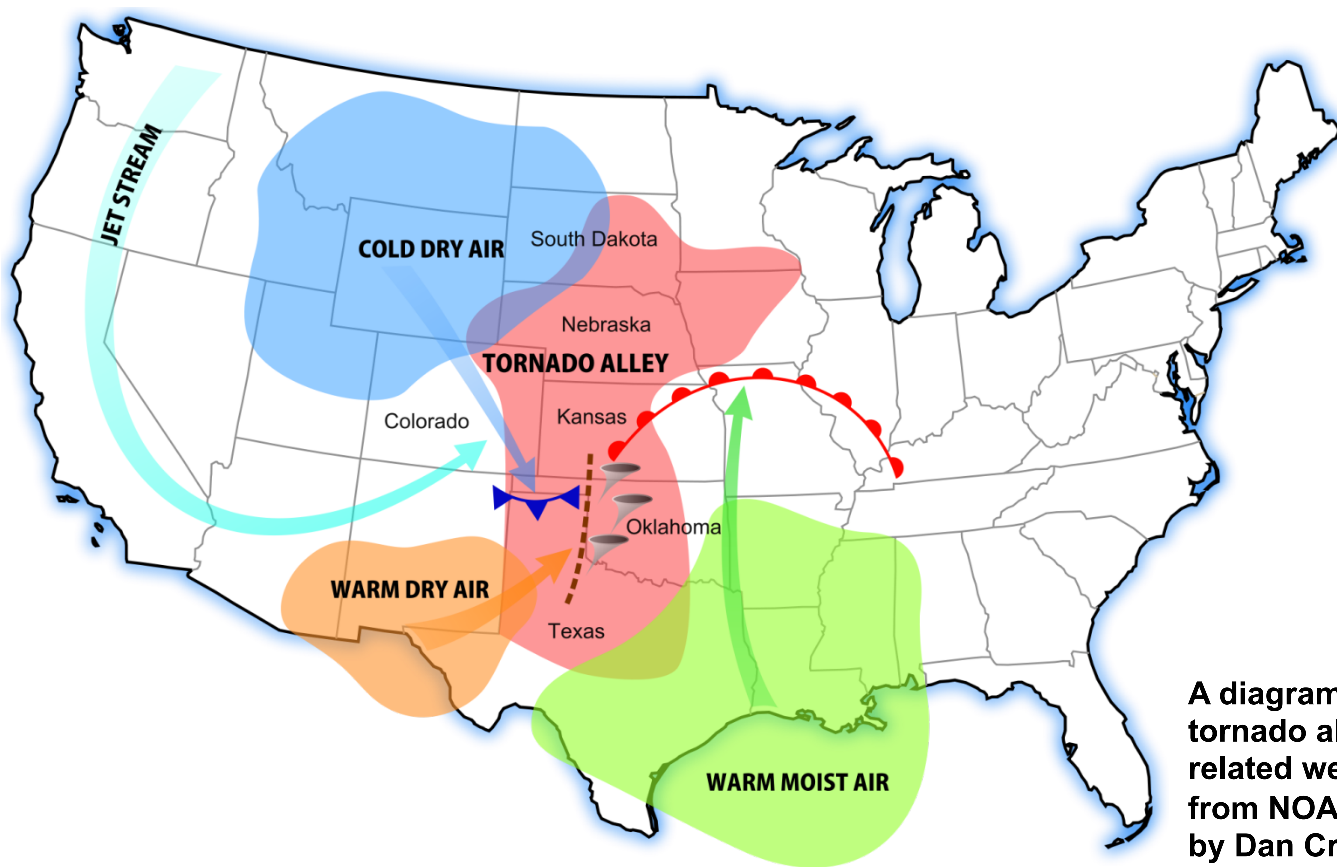
April-May, 2011 U.S. Tornado Outbreak

April 27, 2011 Tuscaloosa, Alabama

April 29, 2011 Tuscaloosa, Alabama

- **In April and May of 2011, a record breaking 1,084 tornadoes and 541 tornado-related fatalities were confirmed in the U.S.**
- **2011 (541) was one of the four deadliest tornado years in the U.S. history along with 1925 (794), 1936 (552) and 1917 (551).**
- **Questions were raised as to whether the extreme tornadoes outbreaks could be linked to long-term climate variability.**

Environmental factors for U.S tornadoes



A diagram of the location of tornado alley and the related weather systems from NOAA SPC (Art work by Dan Craggs)

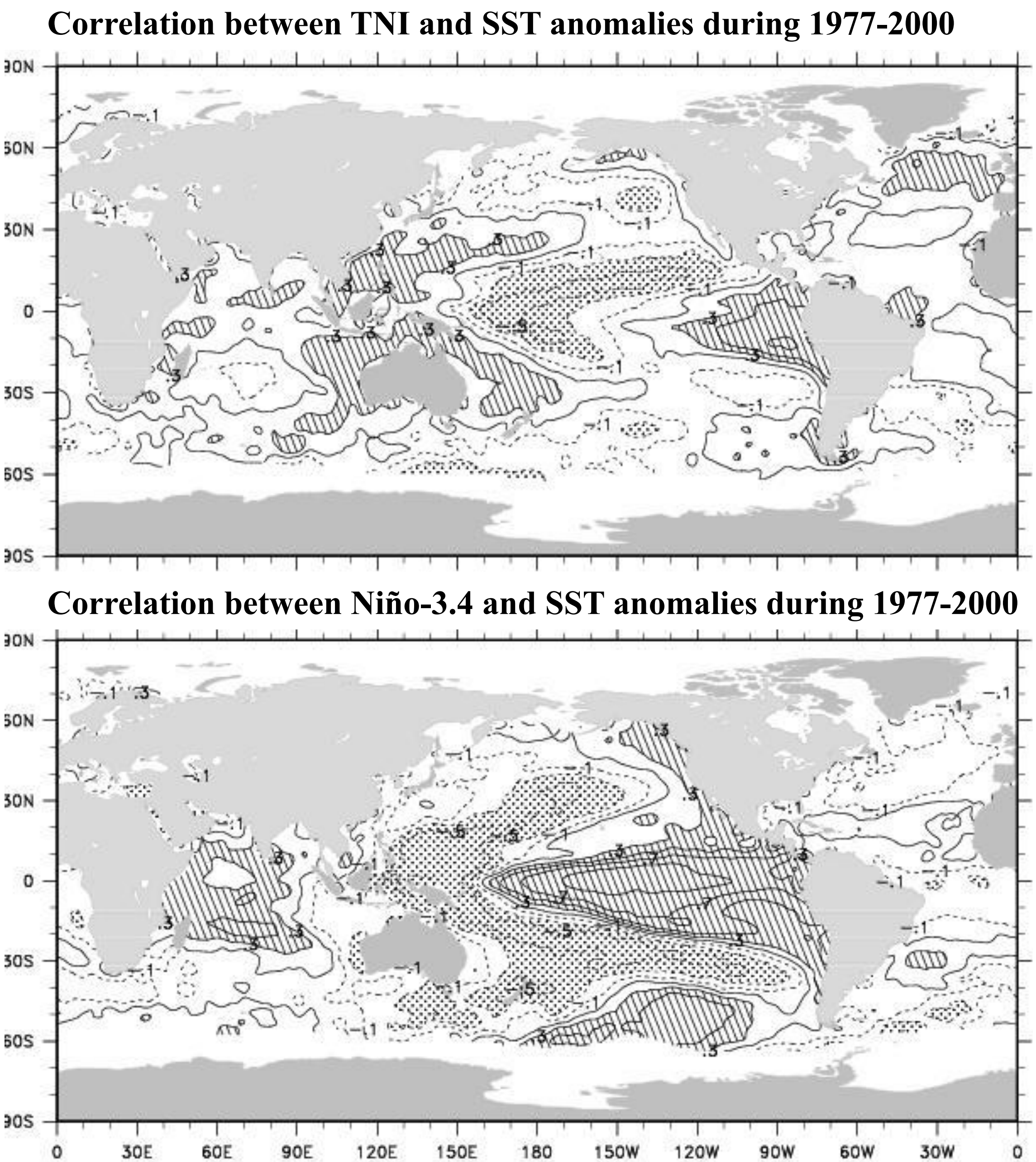
- In the central U.S. east of the Rocky Mountains, cold and dry upper-level air from the high-latitudes often converges with warm and moist lower-level air coming from the Gulf of Mexico.
- Due to this large-scale differential advection, a conditionally unstable atmosphere with high CAPE is formed. The associated lower-level vertical shear further provides a favorable environment to form an intense rotating thunderstorm known as a supercell.

U.S. Tornado Activity and Climate Indices

Index	DJF	FMA	AM
GoM-to-U.S. moisture transport	0.12 (0.09)	0.20 (0.10)	0.44 (0.34)
Lower-Level vertical wind shear	0.12 (0.09)	0.20 (0.12)	0.44 (0.35)
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)

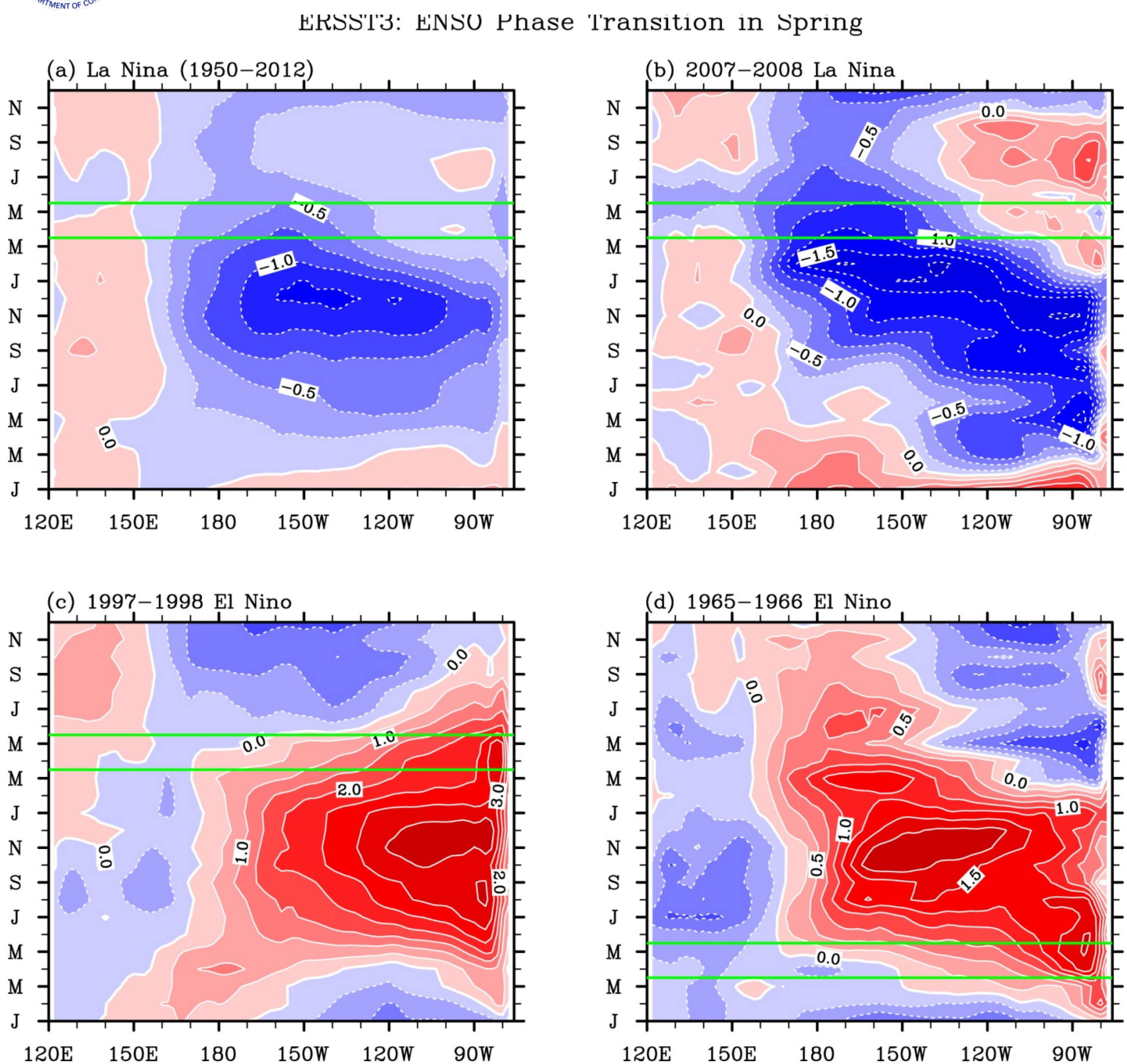
- Correlation coefficients of various long-term climate patterns with the number of intense (F3-F5) tornadoes during the most active tornado months of April and May (AM)
- Niño–3.4 has a very weak correlation with U.S. Tornado activity, consistent with previous studies.
- Niño–4 is negatively correlated, while Niño-1+2 is positively correlated.
- U.S. tornado activity is more strongly correlated with Trans-Niño (TNI) than any other climate pattern.

What is Trans-Niño (TNI)?



- TNI is defined as the difference in normalized SST anomalies between the Niño-1+2 and Niño-4 regions [Trenberth and Stepaniak, 2001].
- It represents the evolution of ENSO during its onset and decaying phases, which frequently occur in boreal spring.
- Why is the number of intense U.S. tornadoes in AM significantly correlated with the TNI index, but not with conventional ENSO?

ENSO Phase Transition in Spring



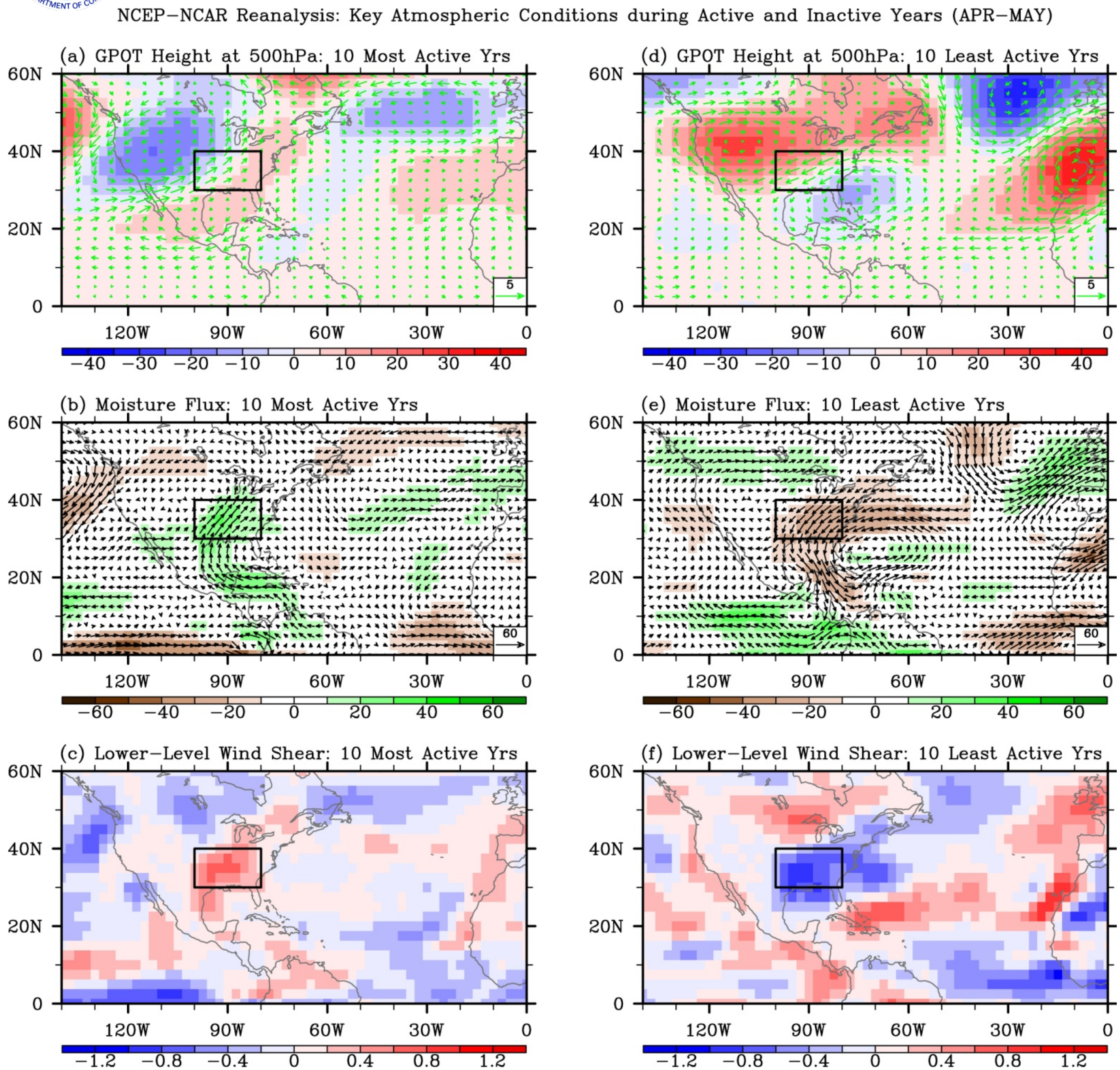
- **A positive TNI typically occurs during the decay phase of La Niña.**
- **But, it can also occur during the onset phase of El Niño.**
- **But, such a case has rarely occurred since 1980s [McPhaden and Zhang 2009].**
- **A positive TNI can also occur during the decay phase of a strong El Nino: 1982-1993 & 1997-1998.**

Trans-Niño and U.S. Tornado Activity

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)

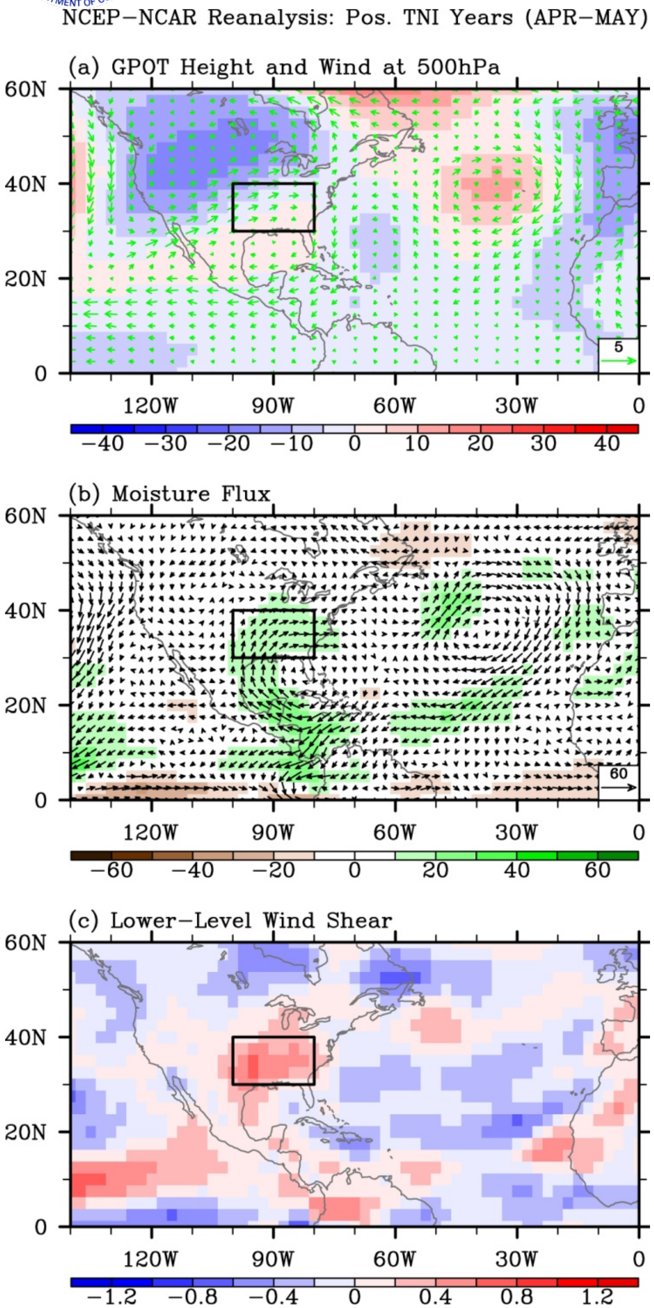
- **However, correlation analysis may not be so useful.**
- **Top 10 extreme tornado outbreak years during 1950-2010 are listed in the table.**
- **7 out of the top 10 extreme tornado years are identified with positive phase (within the upper quartile) TNI.**
- **The top 3 years (1974,1965 and 1957) are also identified with positive phase (within the upper quartile) TNI.**
- **The 10 least active tornado years are largely neutral TNI years (not shown).**

Key Atmos. Conditions for U.S. Tornado Outbreaks



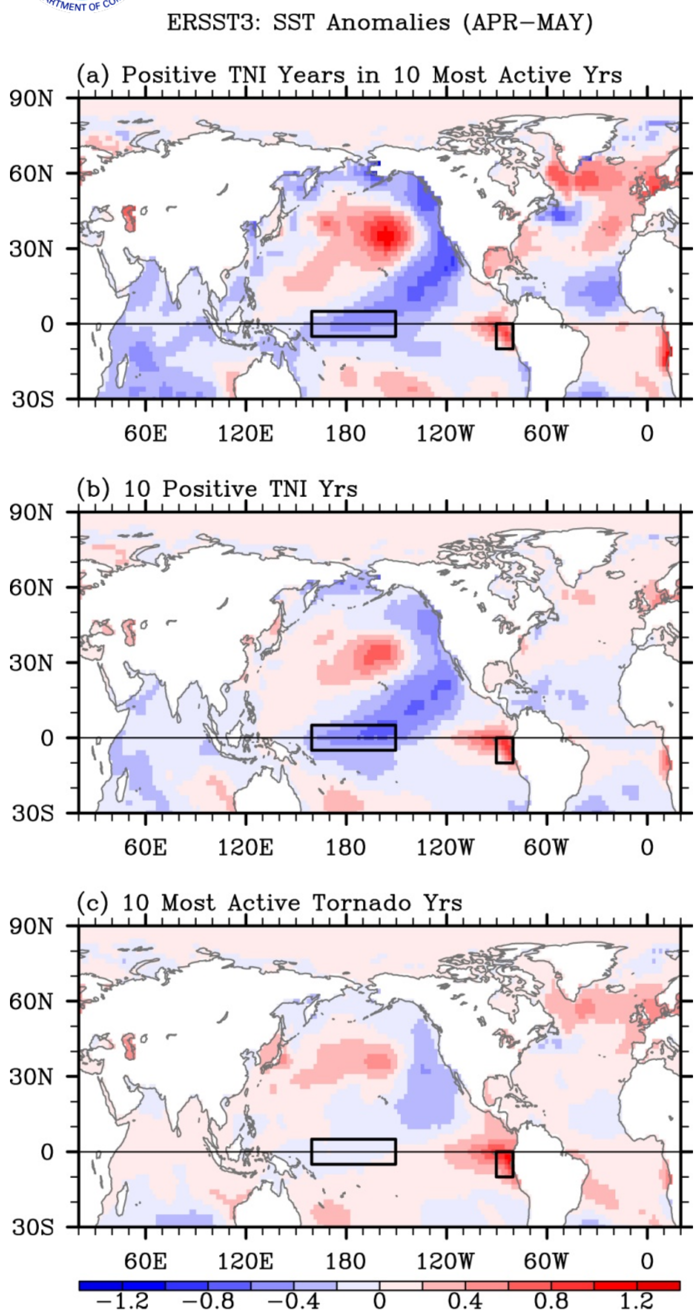
- **Anomalous upper-level cyclone over the North America brings more cold and dry upper-level air to the east of the Rockies.**
- **Increased GoM-to-U.S. lower-level wind (i.e., GPLLJ) and associated moisture transport.**
- **Enhanced large-scale differential advection leads to increased CAPE and vertical wind shear east of the Rockies.**

Trans-Niño and U.S. Tornado Activity



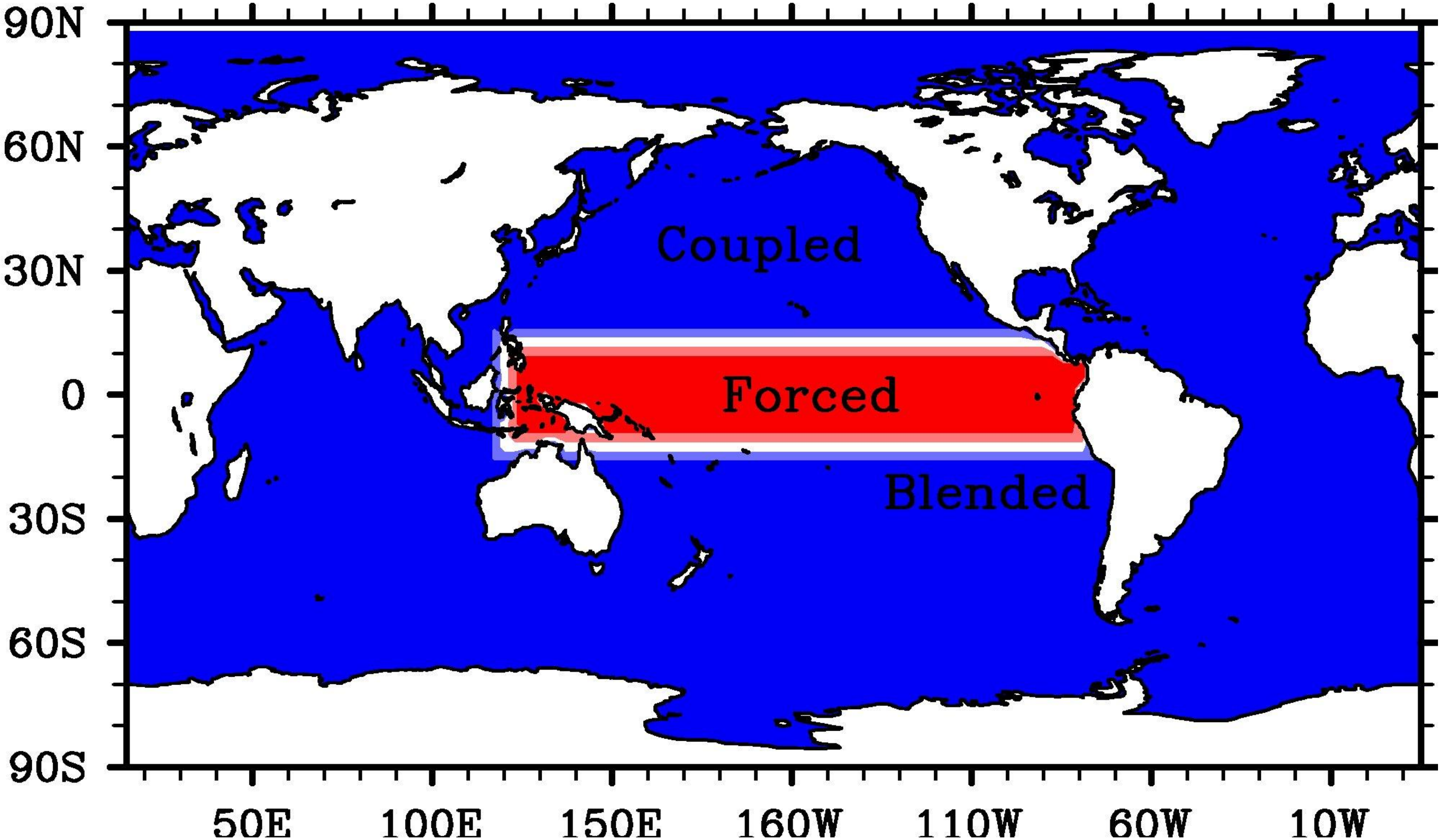
- Key atmospheric conditions for the top 10 positive TNI years are shown.
- Anomalous upper-level cyclone over the North America brings more cold and dry upper-level air to the east of the Rockies.
- Increased GoM-to-U.S. lower-level wind (i.e., GPLLJ) and associated moisture transport.
- Enhanced large-scale differential advection leads to increased CAPE and vertical wind shear east of the Rockies.
- All these conditions are consistent with those for the top 10 extreme tornado outbreak years.

Trans-Niño and U.S. Tornado Activity



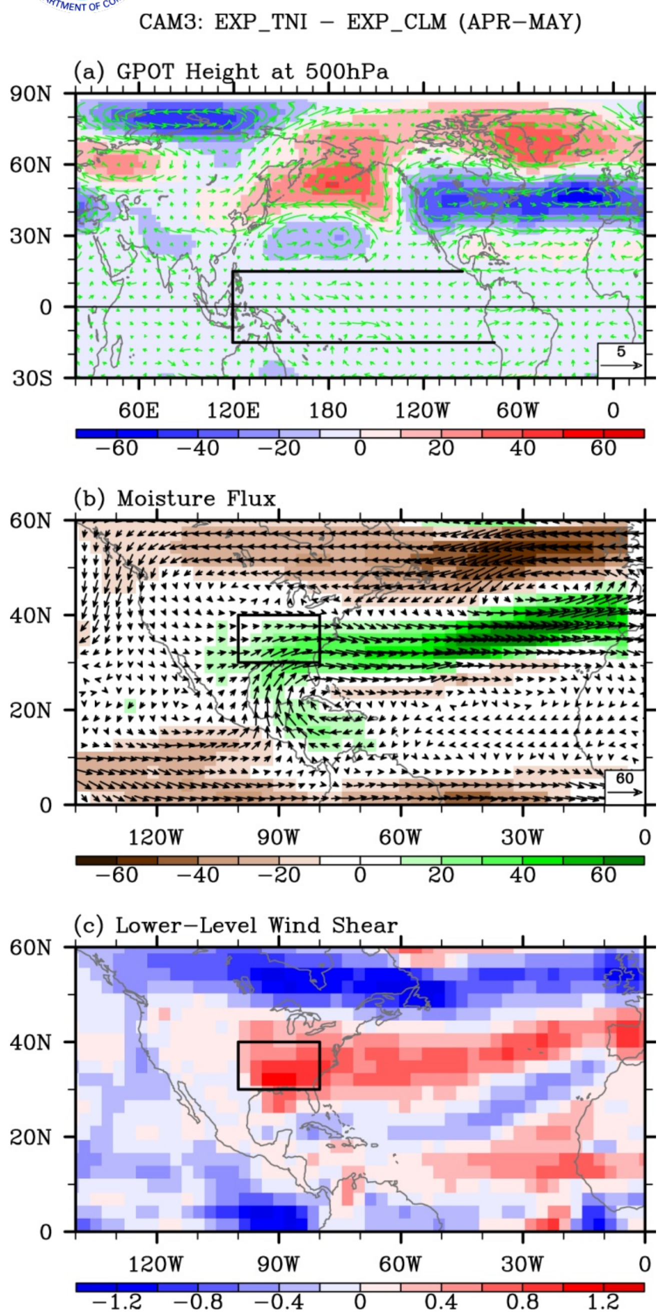
- **SST anomalies for 5 positive TNI years identified among the 10 most active tornado years are shown in the upper panel.**
- **SST anomalies for 10 positive TNI years and for the 10 most active tornado years are shown in the middle and upper panels.**
- **Positive Trans-Niño occurs when normalized SST anomalies are larger in Niño-1+2 than in Niño–4 region [Trenberth and Stepaniak 2001].**
- **Therefore, neutral Niño–4 with positive Niño–1+2 and neutral Niño–1+2 with negative Niño–4 are also qualified as positive TNI conditions.**

Model Experiments (CAM3-SOM)



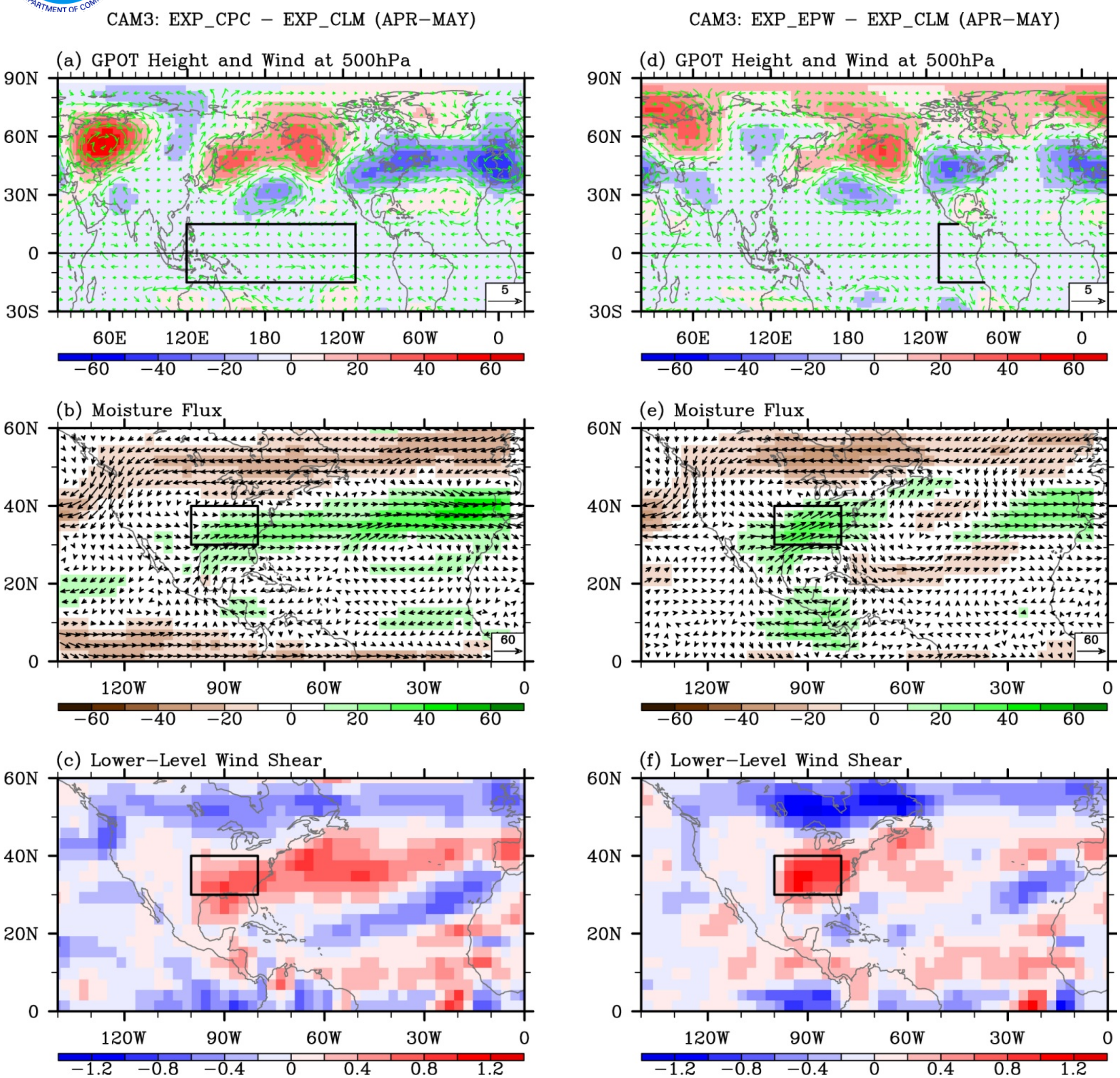
- **The same methodology was previously used in Lee et al. [2008] for studying ENSO teleconnection to the tropical North Atlantic region.**

Model Experiments (CAM3-SOM)



- Key atmospheric conditions for EXP_TNI are shown.
- Anomalous upper-level cyclone over the North America brings more cold and dry upper-level air to the east of the Rockies.
- Increased GoM-to-U.S. lower-level wind and associated moisture transport.
- All these conditions are consistent with the observations.

Model Experiments (CAM3-SOM)



- **EXP_CPC: Same as EXP_TNI except that SST anomalies in EP are kept neutral.**
- **EXP_EPW: Same as EXP_TNI except that SST anomalies in the CP are kept neutral.**
- **In both cases, all three conditions are favorable for increased U.S. tornado activity.**
- **Why EXP_CPC and EXP_EPW have a similar influence on the U.S?**

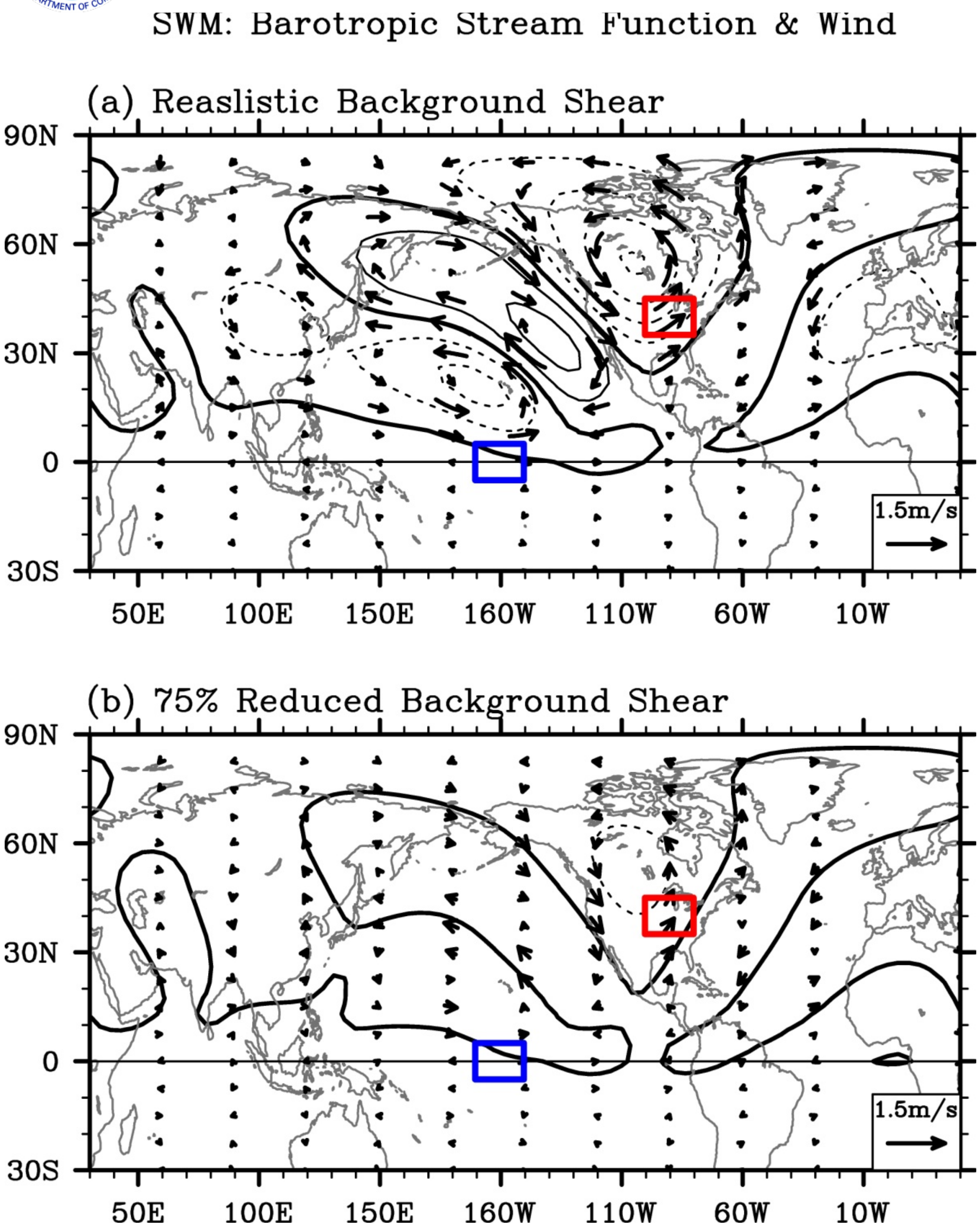
Background Wind Shear & Teleconnection

$$\overline{U}\frac{\partial\overline{\xi}}{\partial x}+\left(\beta-\frac{d^2\overline{U}}{dy^2}\right)\overline{v}=-r_0\overline{\xi}+A_0\nabla^2\overline{\xi}+F_{\overline{\xi}}$$

$$F_{\overline{\xi}}=\hat{v}\frac{d^2\hat{U}}{dy^2}+\frac{d\hat{U}}{dy}\left(\frac{\partial\hat{u}}{\partial x}+\frac{\partial\hat{v}}{\partial y}\right)-\hat{U}\frac{\partial\hat{\xi}}{\partial x}$$

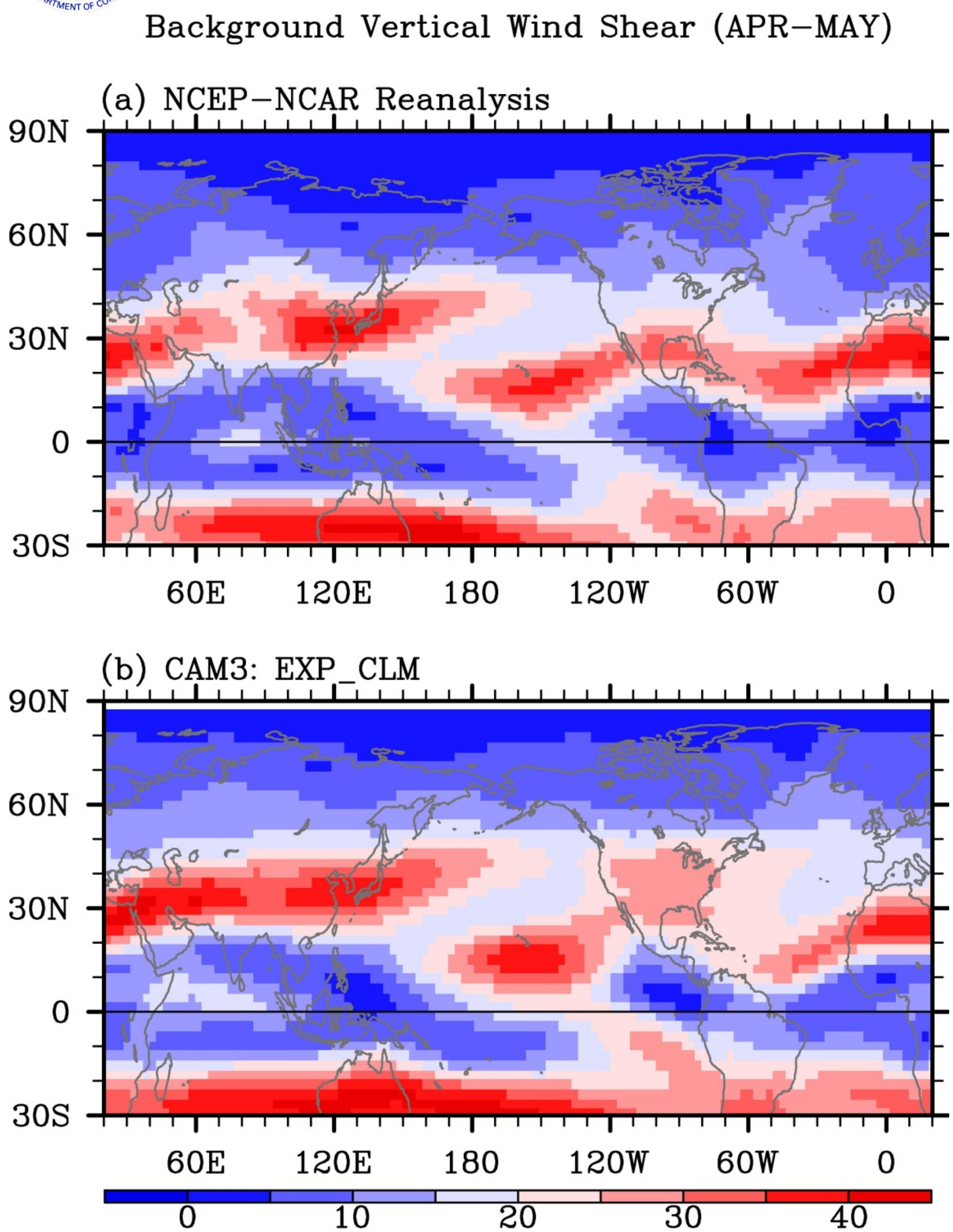
- **As shown in earlier theoretical studies, the background vertical wind shear is one of the two critical factors required for tropical heating to radiate barotropic teleconnections to the high-latitudes [e.g., Webster 1981; Kasahara and da Silva Dias 1986; Lee et al. 2009].**
- **The so-called Rossby wave source term for the barotropic vorticity equation (linearized with background mean flow) is determined by the background vertical wind shear.**

Background Wind Shear & Teleconnection



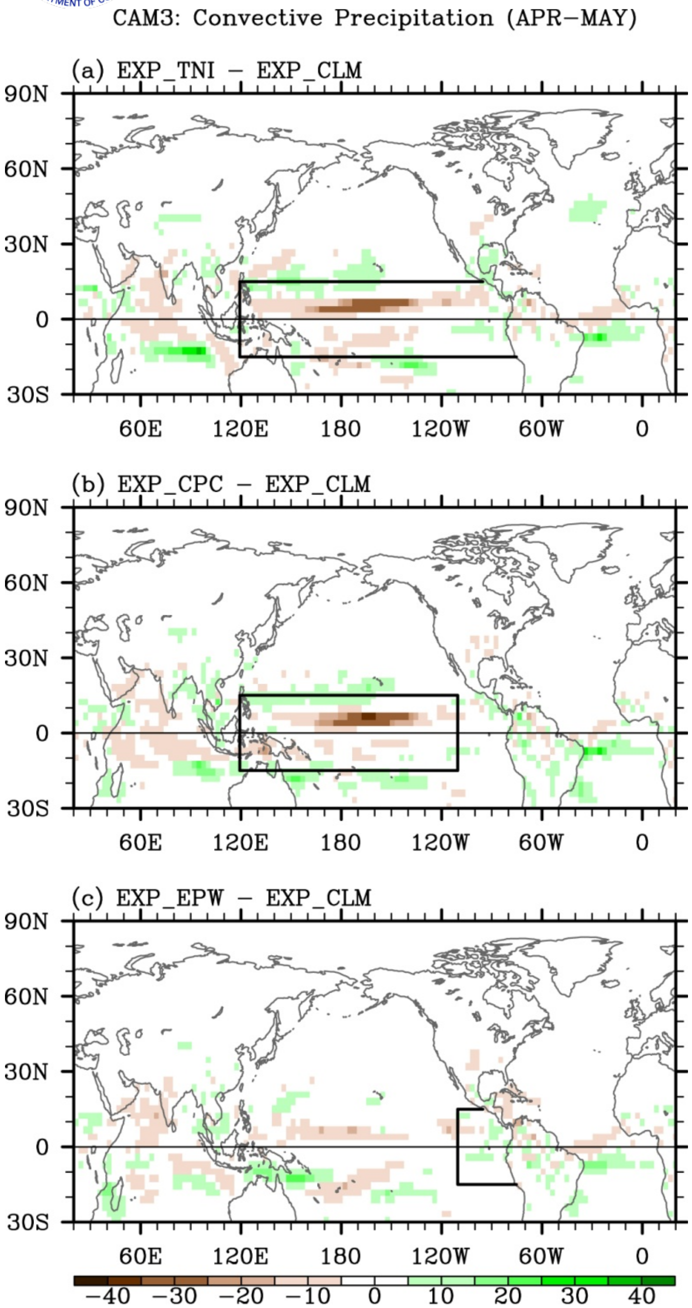
- **Two-level model of Lee et al. [2009], linearized with an idealized background flow in AM, is forced with cooling in CP.**
- **PNA-like teleconnection pattern emanates from CP to enhance the large-scale differential advection in the central U.S.**
- **When the background shear is decreased by 75%, while the background barotropic wind is kept the same, the PNA-like teleconnection pattern almost disappears.**
- **See Lee et al. [2009] and references therein for more discussions on this issue.**

Background Wind Shear & Teleconnection



- **In both observations and EXP_CLM, the background vertical wind shear between 200 and 850hPa in AM is largest in the central tropical North Pacific and smallest in EP and the western tropical Pacific (WP).**
- **The spatial pattern of the background wind shear in the tropical Pacific suggests that the Rossby wave train in EXP_EPW is not directly forced in EP.**
- **What forced the Rossby wave train in EXP_EPW?**

Background Wind Shear & Teleconnection



- In EXP_EPW, convection is increased locally in EP, but it is decreased in CP as in EXP_CPC.
- Increased convection in EP suppresses convection in CP that in turn forces a negative phase PNA-like pattern.
- Cooling in CP and warming in EP may have a constructive influence on the teleconnection pattern.
- Perhaps, reduced convection in the CP can be explained as Rossby wave response to warm SST anomalies in the EP [Gill 1980].
- Cooling in CP with neutral SST anomalies in EP or warming in EP with neutral SST anomalies in CP can strengthen the large-scale differential advection over the central U.S.

Summary

- Observations and reanalysis products are used to show that a positive phase of the Trans-Niño is linked to U.S. tornado outbreaks.
- The link between the Trans-Niño and U.S. tornado outbreaks is due to the enhanced large-scale differential advection during a positive phase of the Trans-Niño:
  1) anomalous upper-level cyclone over the North America;
  2) increased GoM-to-U.S. moisture transport;
  3) increased lower-level vertical wind shear east of the Rockies.
- Modeling experiments suggest that warm SST anomalies in the EP work constructively with cold SST anomalies in the CP to force a strong and persistent teleconnection pattern that enhances large-scale differential advection.
- Lee S.-K., R. Atlas, D. B. Enfield, C. Wang and H. Liu, 2012. Is there an optimal ENSO pattern that enhances large-scale atmospheric processes conducive to major tornado outbreaks in the U.S.? *J. Climat.*, In-press.

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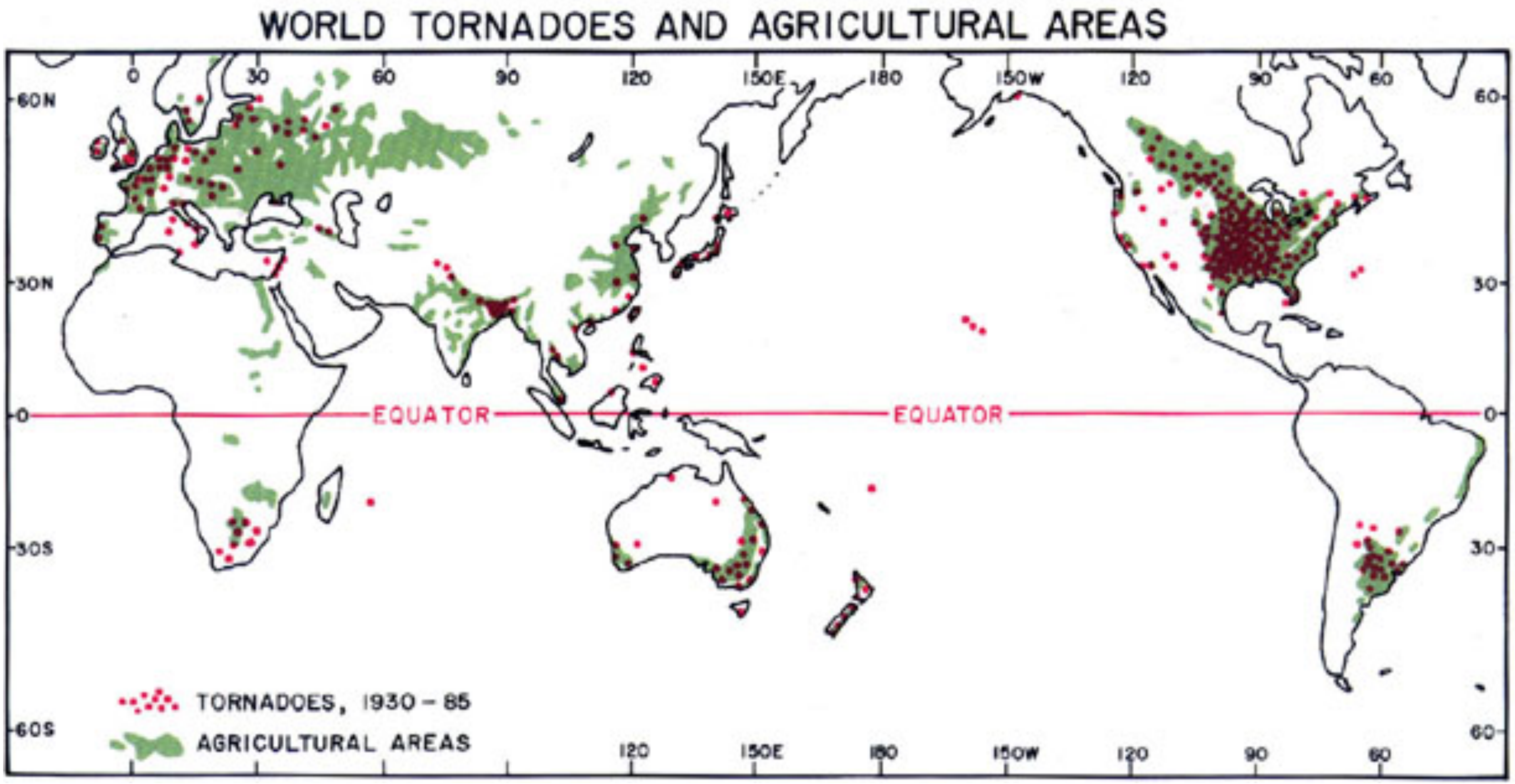
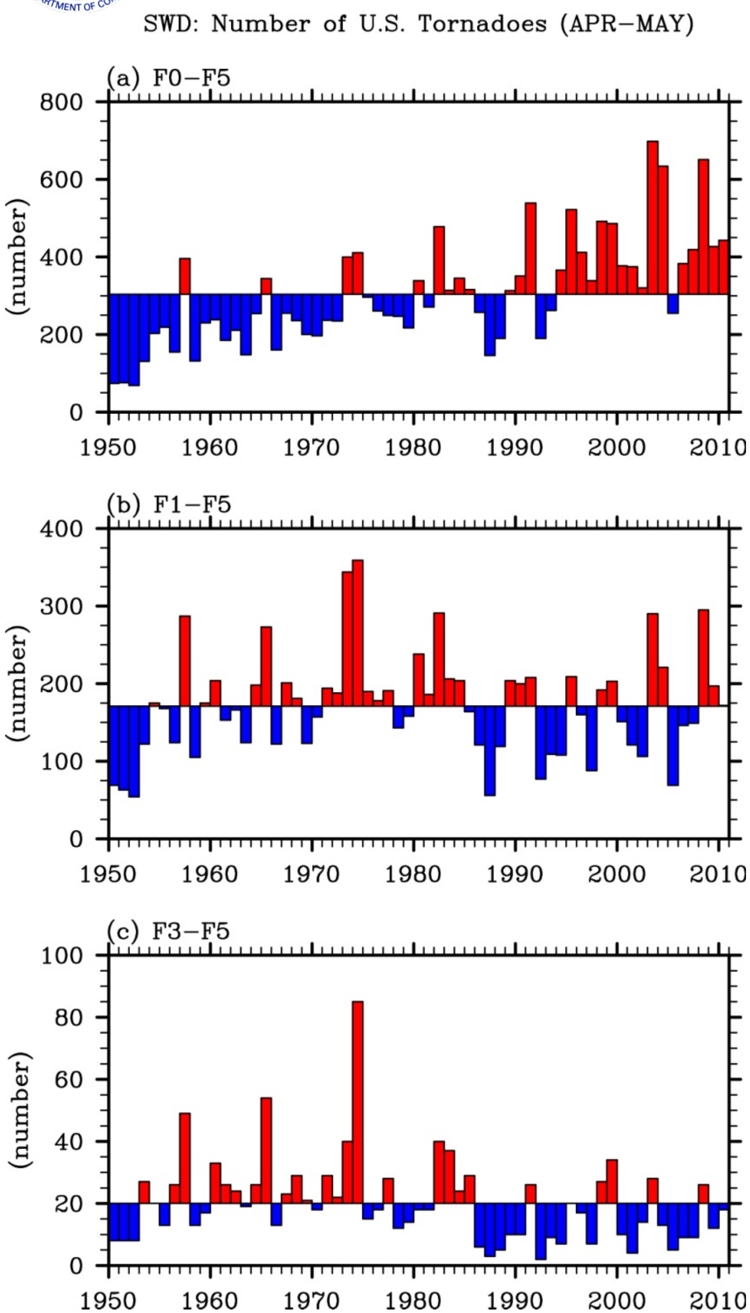
Global Map of Tornado Frequency



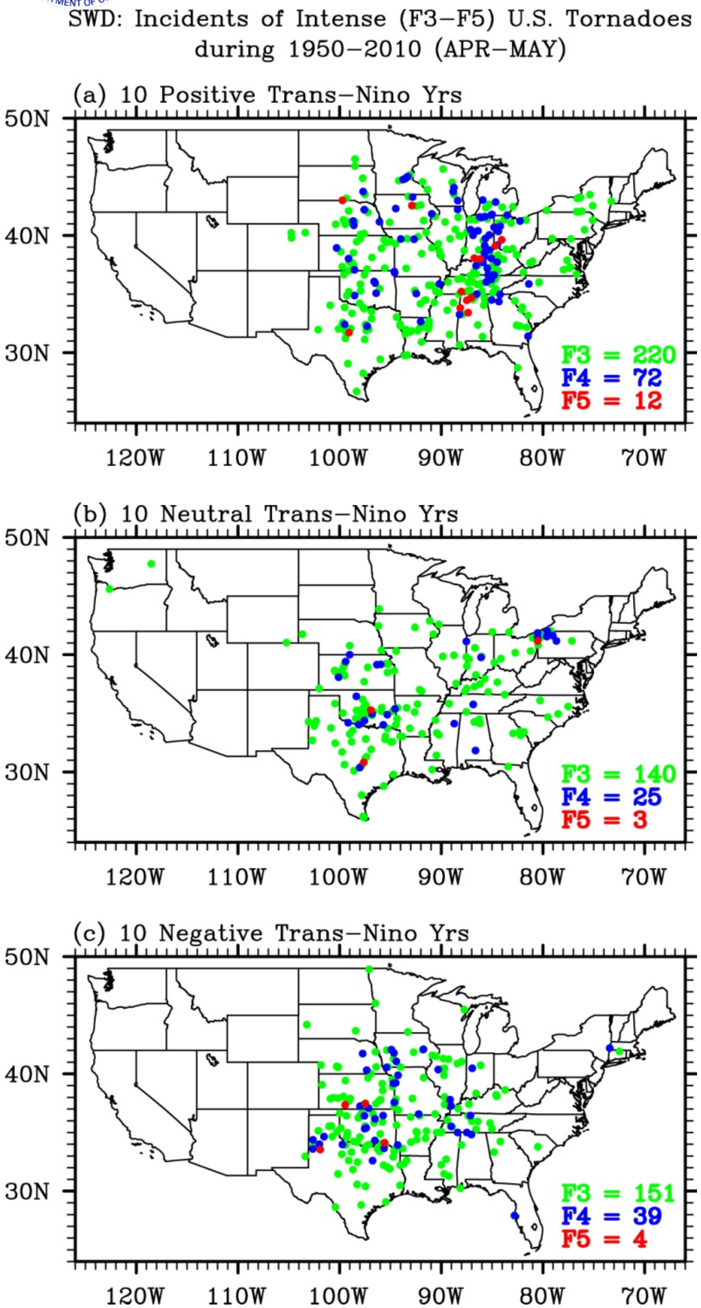
- Tornadoes are more common in the U.S. than in any other country in the world.
- During the last two decades, 938 ~ 1820 tornadoes have occurred in the U.S. annually.

Is U.S Tornado Activity Increasing?



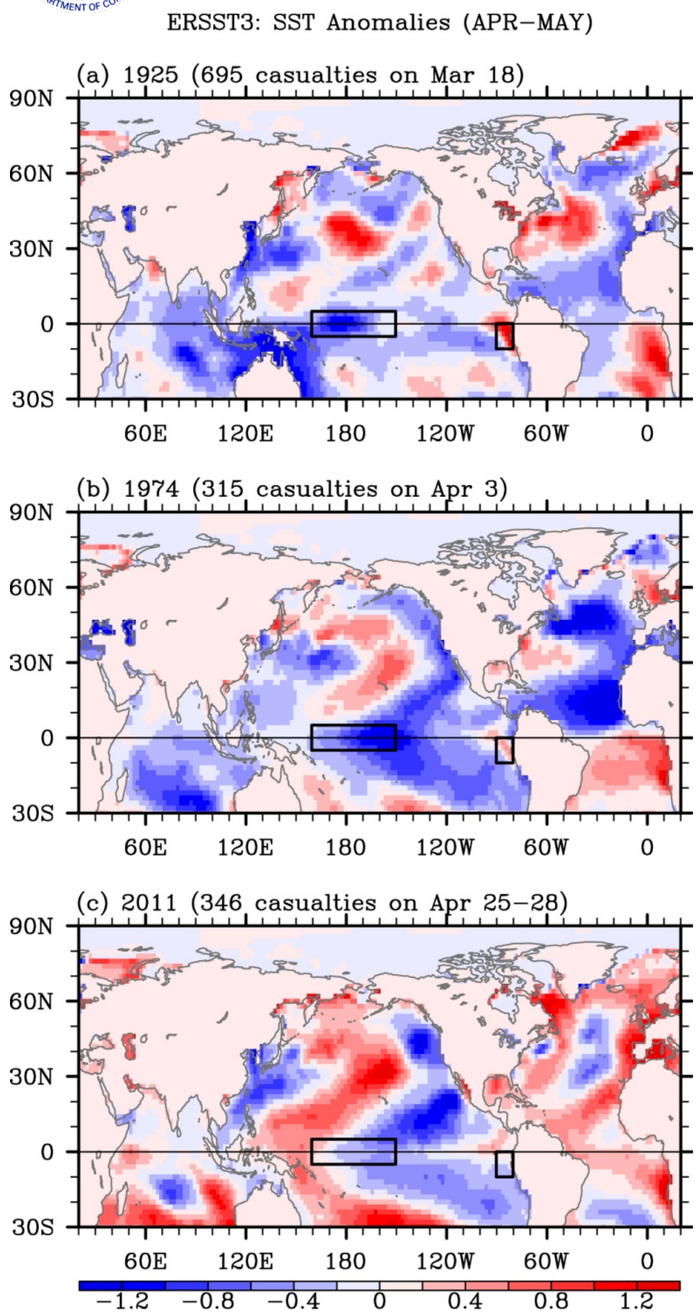
- The number of total U.S. tornadoes (F0-F5) during the most active tornado months of April and May (AM) has been steadily increasing since 1950.
- However, tornado database, especially in earlier periods, has many issues.
- Once F0 tornadoes are removed, the positive trend disappears.
- Intense and 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.
- Here, we use the number of intense U.S. tornadoes (F3-F5) in AM as the primary diagnostic index in this study.
- Intense tornado-days is also used as an index.

Trans-Niño and U.S. Tornado Activity



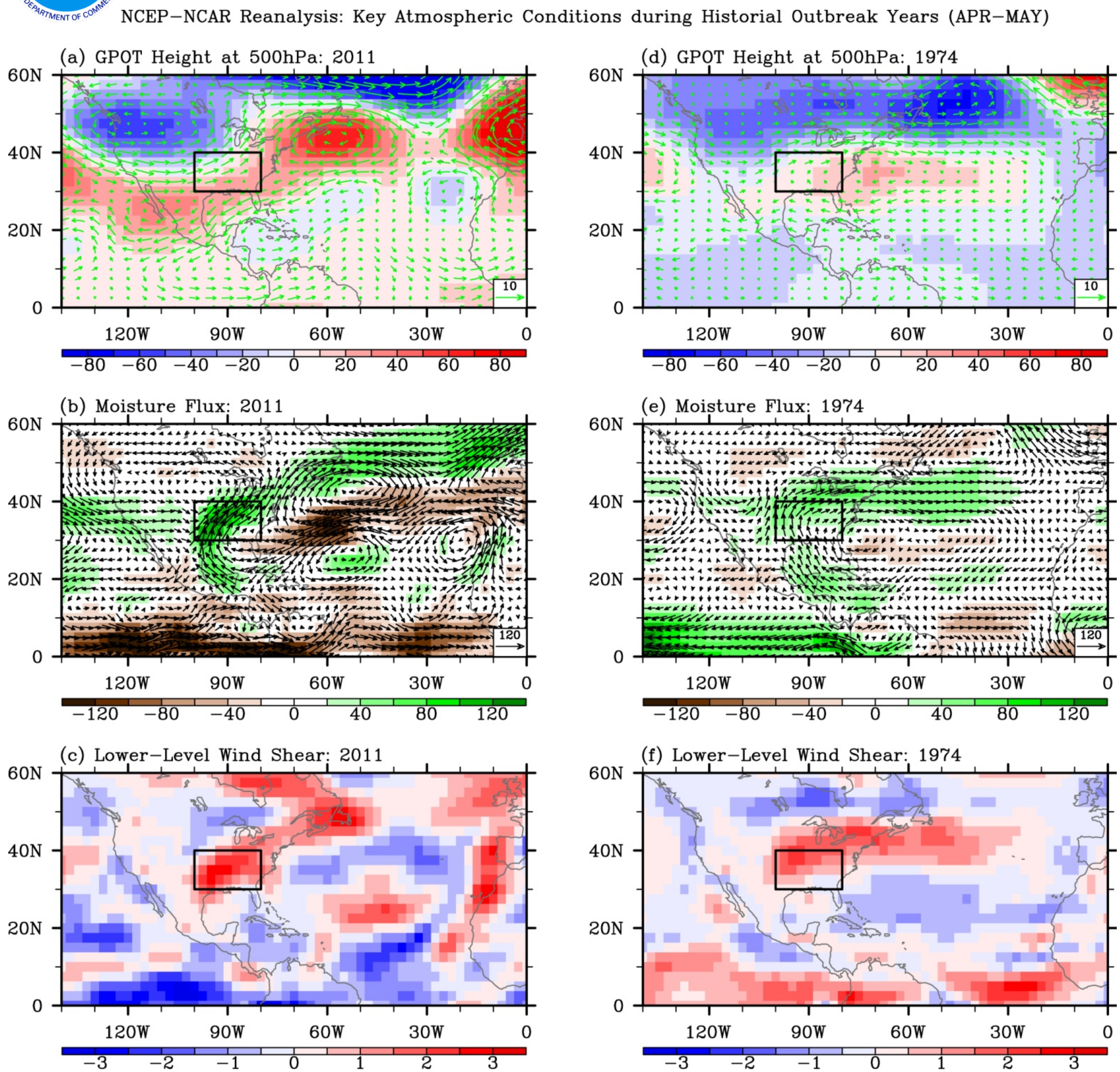
- **Incidents of intense (F3-F5) tornadoes for 10 positive, 10 neutral and 10 negative Trans-Niño years during 1950-2010 are shown.**
- **Number of intense tornadoes is increased from 168 during the 10 neutral TNI years to 304 during the 10 positive TNI years (It is almost doubled).**
- **During positive TNI years, violent (F4-F5) tornadoes are increased over the Ohio river valley.**
- **During negative TNI years, number of intense tornadoes is not increased.**

Trans-Niño and Historical U.S. Tornado Outbreaks



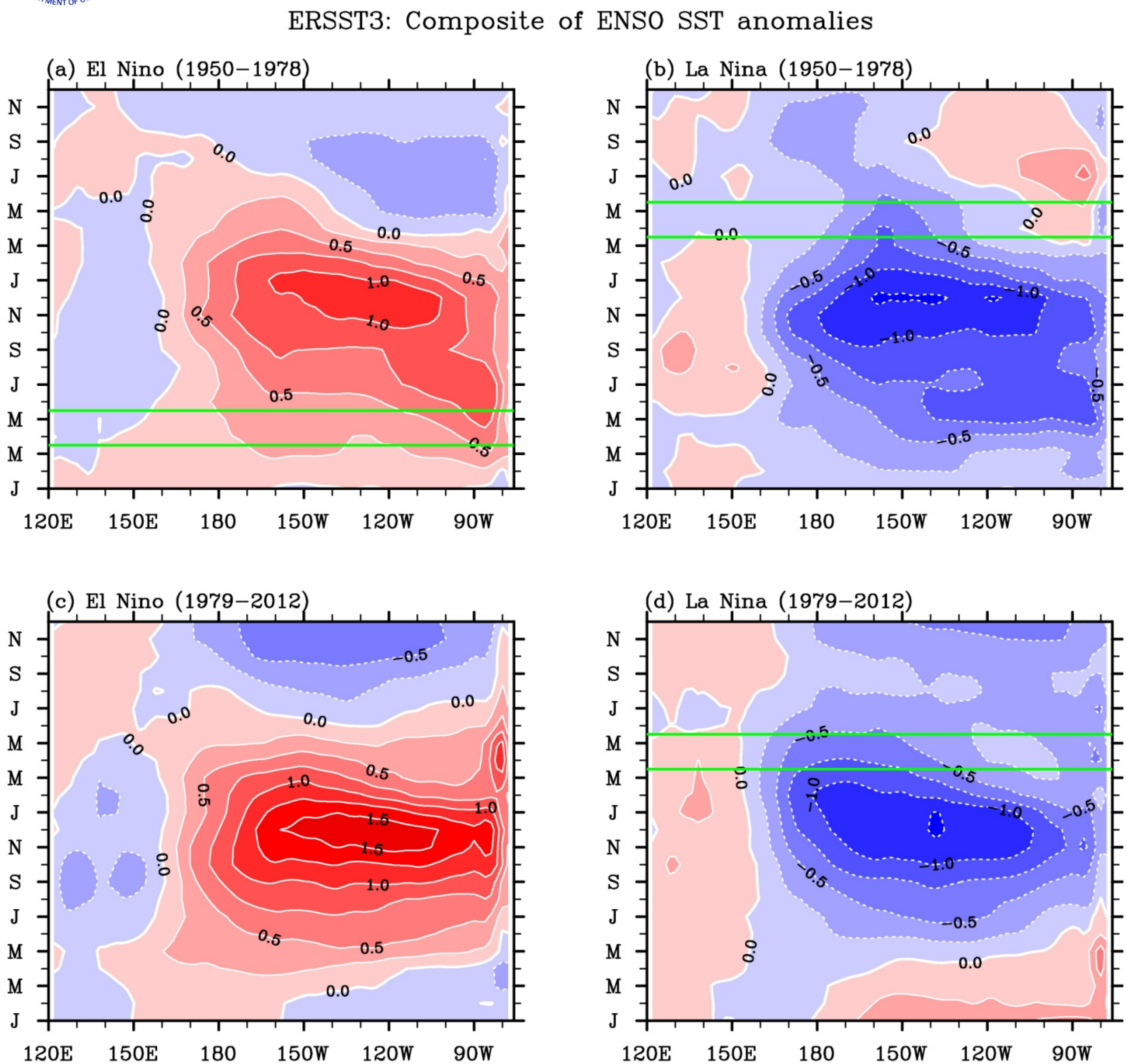
- **Tri-state (Missouri, Illinois and Indiana) tornado of March 18, 1925 is the deadliest tornado outbreak event in the U.S. history (695 deaths).**
- **Super tornado outbreak on April 3, 1974 resulted in 315 deaths.**
- **April 25-28, 2011 is the 2nd deadliest tornado outbreak event (346 deaths).**
- **1936 (552) and 1917 (551) are the 2nd and 3rd deadliest tornado years.**
- **All five of these historic tornado outbreak years were positive Trans-Niño years.**
- **April & March of 1917 is marked as the strongest TNI during the period of 1854 – 2011 (not shown).**

Trans-Niño and Historical U.S. Tornado Outbreaks



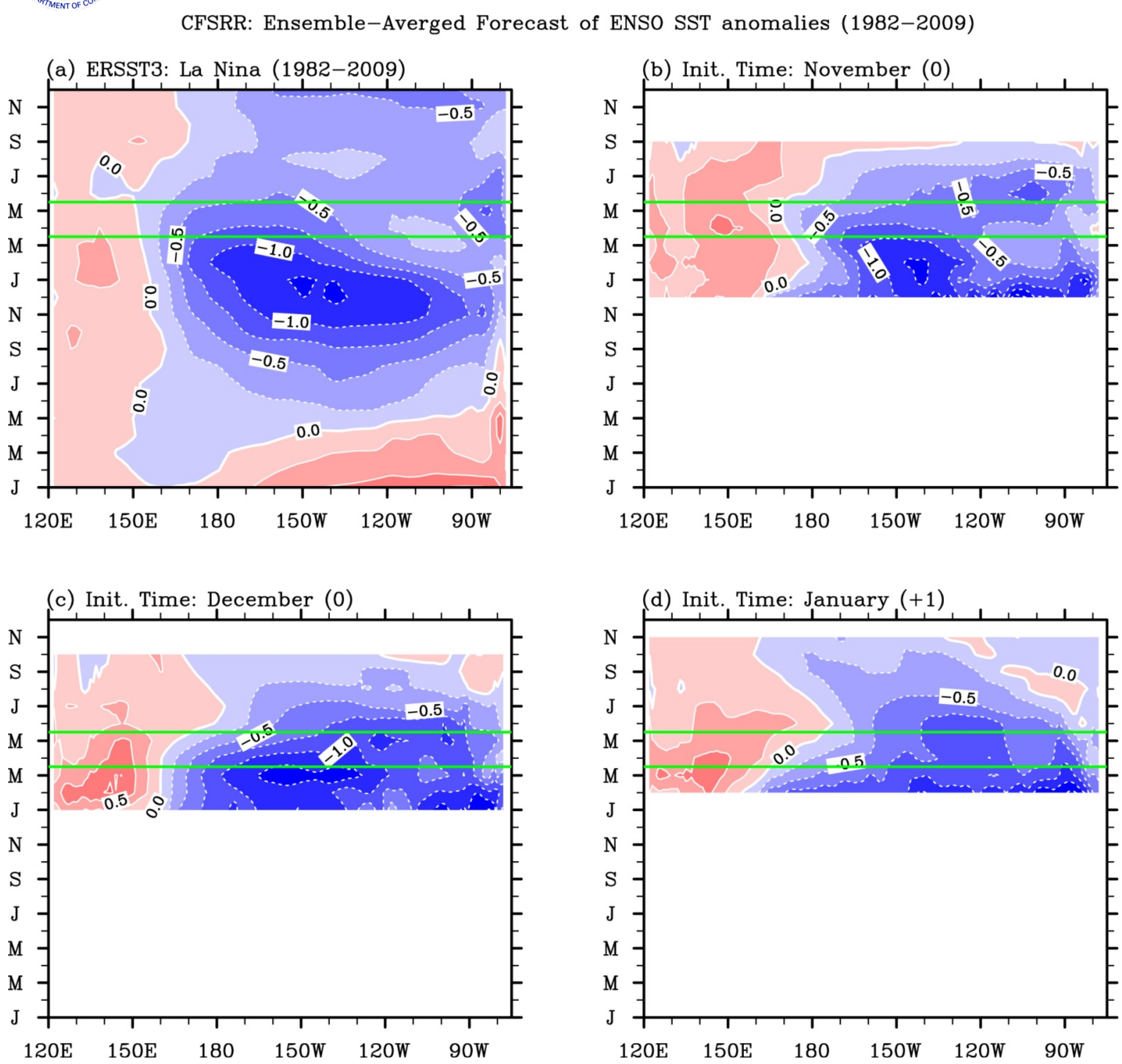
- All three conditions are consistent with those for the 10 positive Trans-Niño years.
- This means that the positive Tran-Niño condition during these historical tornado outbreak years are not just coincident.
- Therefore, it is likely that the positive Trans-Niño condition have contributed to these historical tornado outbreak events.

ENSO Phase Transition in Spring



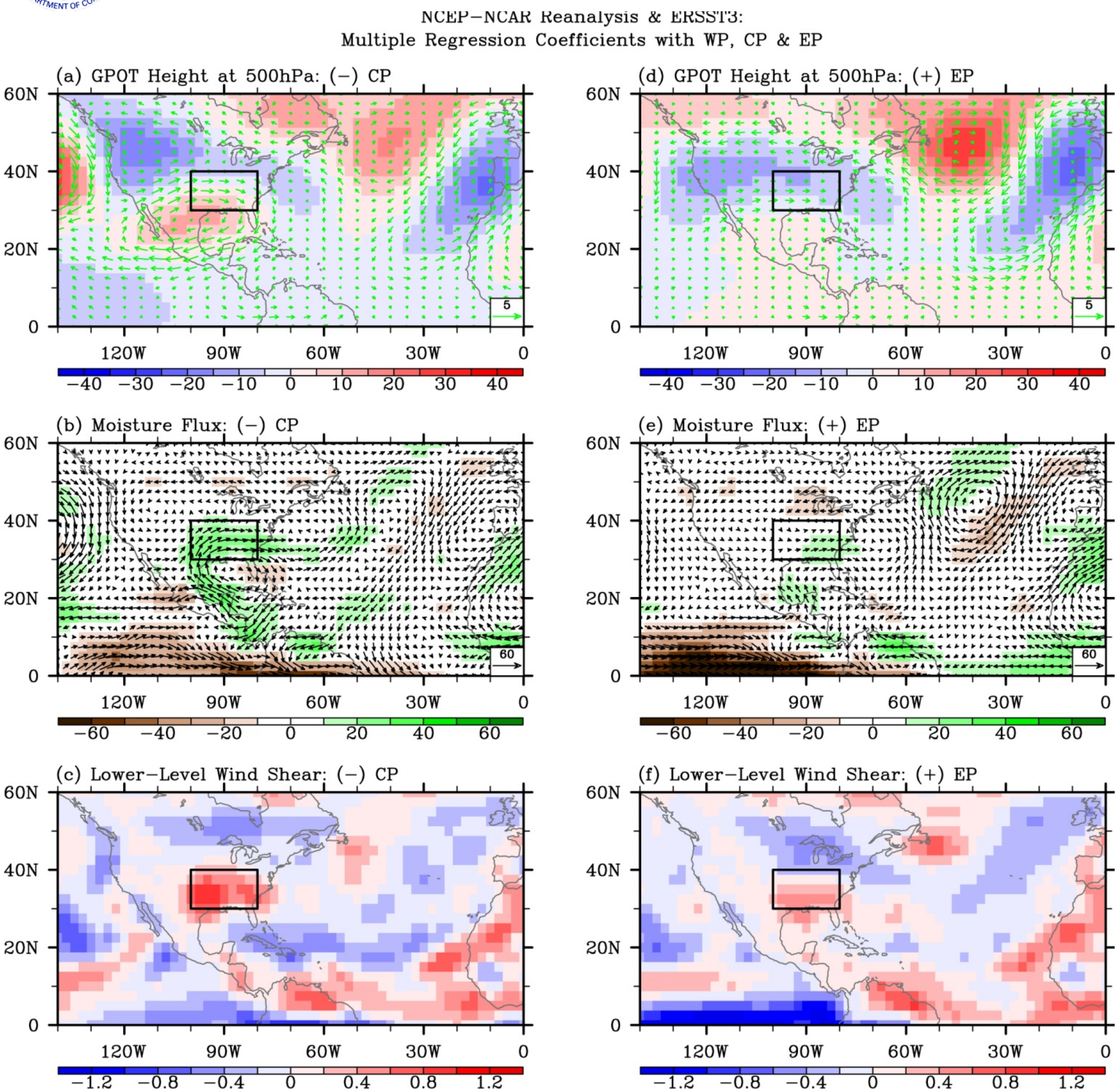
- **Prior to 1976/77, a positive TNI could occur during the onset of an El Niño and the decay of a La Niña.**
- **After 1976/77, a positive TNI occurs only during the decay phase of a La Niña.**
- **Reproduced from McPhaden and Zhang [2009]**

Springtime ENSO Phase Transition Forecast



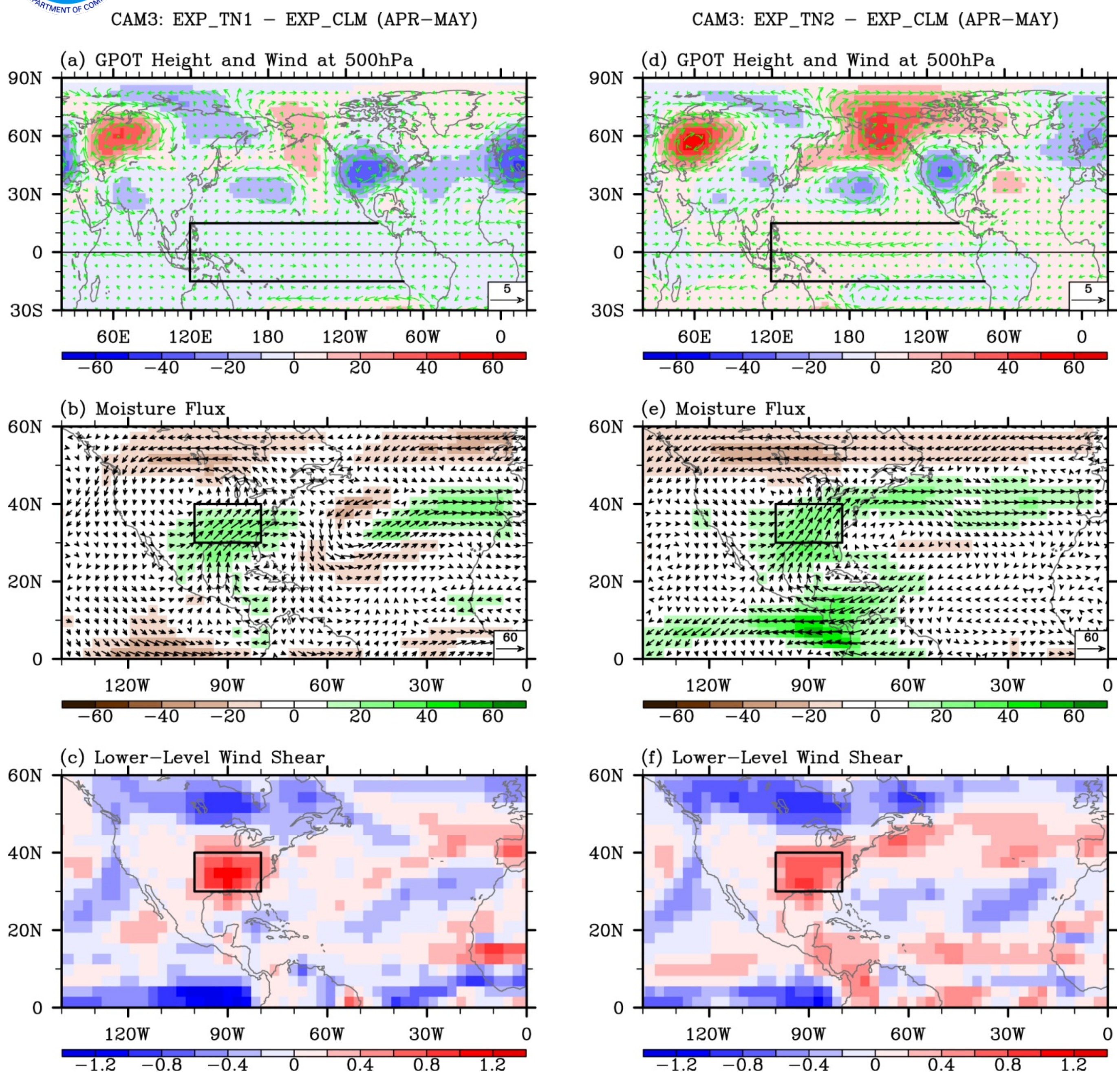
- In general, CFSRR can simulate slower decay of SST anomalies in CP and faster decay in EP during the decay phase of La Niña.
- This tends to deteriorate when the model is initialized in December (0) and January (+1).

Impacts of CPC versus EPW on Teleconnection



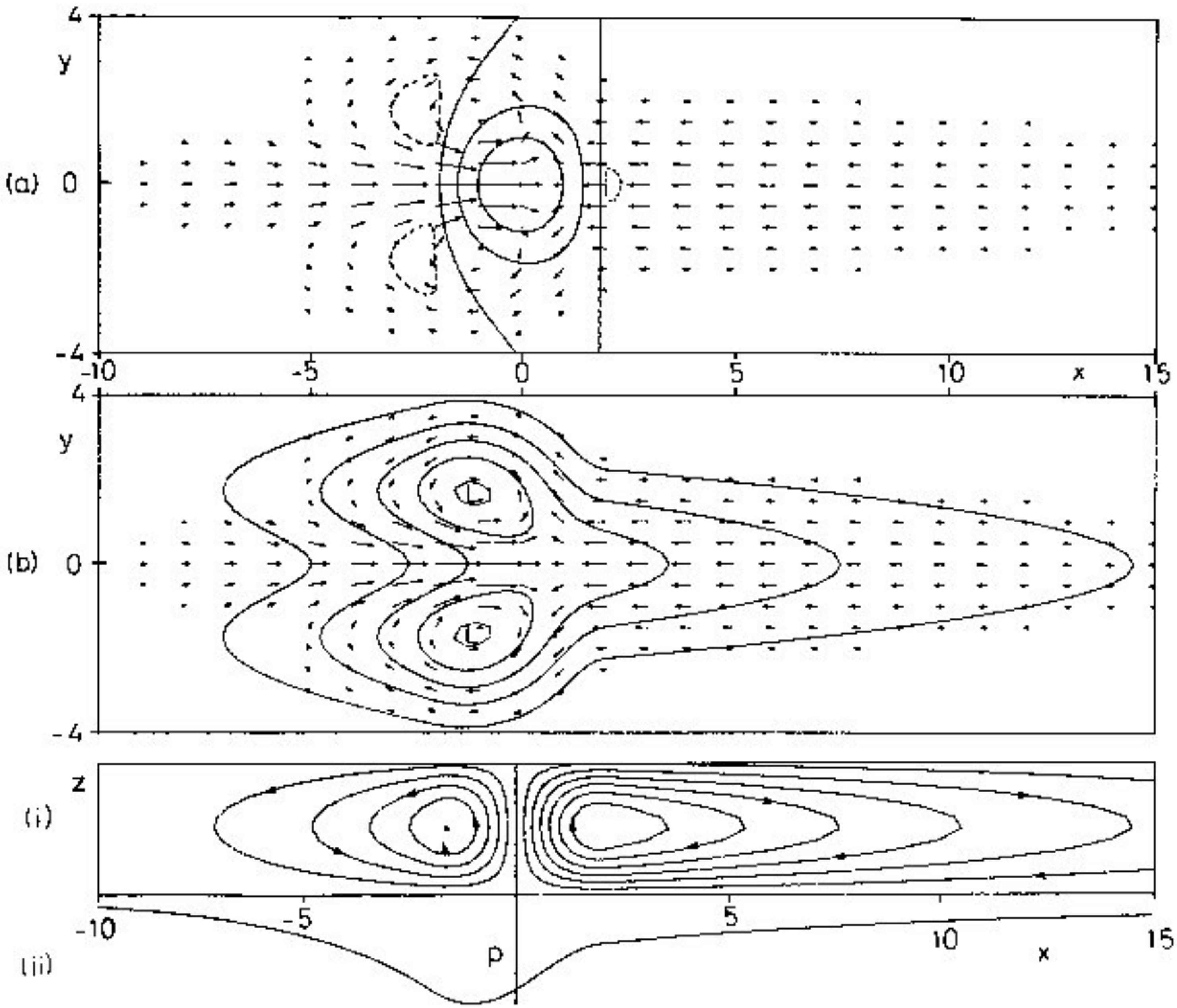
- **Multiple regression coefficients of key atmospheric conditions on WP, CP and EP SST anomalies.**
- **Cold SST anomalies & warm SST anomalies in the EP have somewhat similar effects.**

Model Experiments (CAM3-SOM)



- **Results from EXP_TN1 and EXP_TN2 are shown.**
- **EXP_TN1: Tropical Pacific SSTs are prescribed with the composite of 10 positive TNI years.**
- **EXP_TN2: Tropical Pacific SSTs are prescribed with the composite of 10 most active years.**
- **All three conditions are favorable for increased U.S. tornado activity.**

Impacts of CPC versus EPW on Teleconnection



What is Fujita Scale?

Damage f scale	Little Damage	Minor Damage	Roof Gone	Walls Collapse	Blown Down	Blown Away
	f0	f1	f2	f3	f4	f5

Windspeed F scale

m/s	17 m/s		32		50		70		92		116		142
Windspeed F scale		F0		F1		F2		F3		F4		F5	
mph	40 mph		73		113		158		207		261		319

To convert f scale into F scale, add the appropriate number

Weak Outbuilding	-3	f3	f4	f5	f5	f5	f5
Strong Outbuilding	-2	f2	f3	f4	f5	f5	f5
Weak Framehouse	-1	f1	f2	f3	f4	f5	f5
Strong Framehouse	0	F0	F1	F2	F3	F4	F5
Brick Structure	+1	-	f0	f1	f2	f3	f4
Concrete Building	+2	-	-	f0	f1	f2	f3

Fig. 2.4-1 The Fujita tornado scale (F scale) pegged to damage-causing windspeeds. The extent of damage expressed by the damage scale (f scale) varies with both windspeed and the strength of structures.