What caused the quad-states tornado outbreak on 10-11 December 2021?

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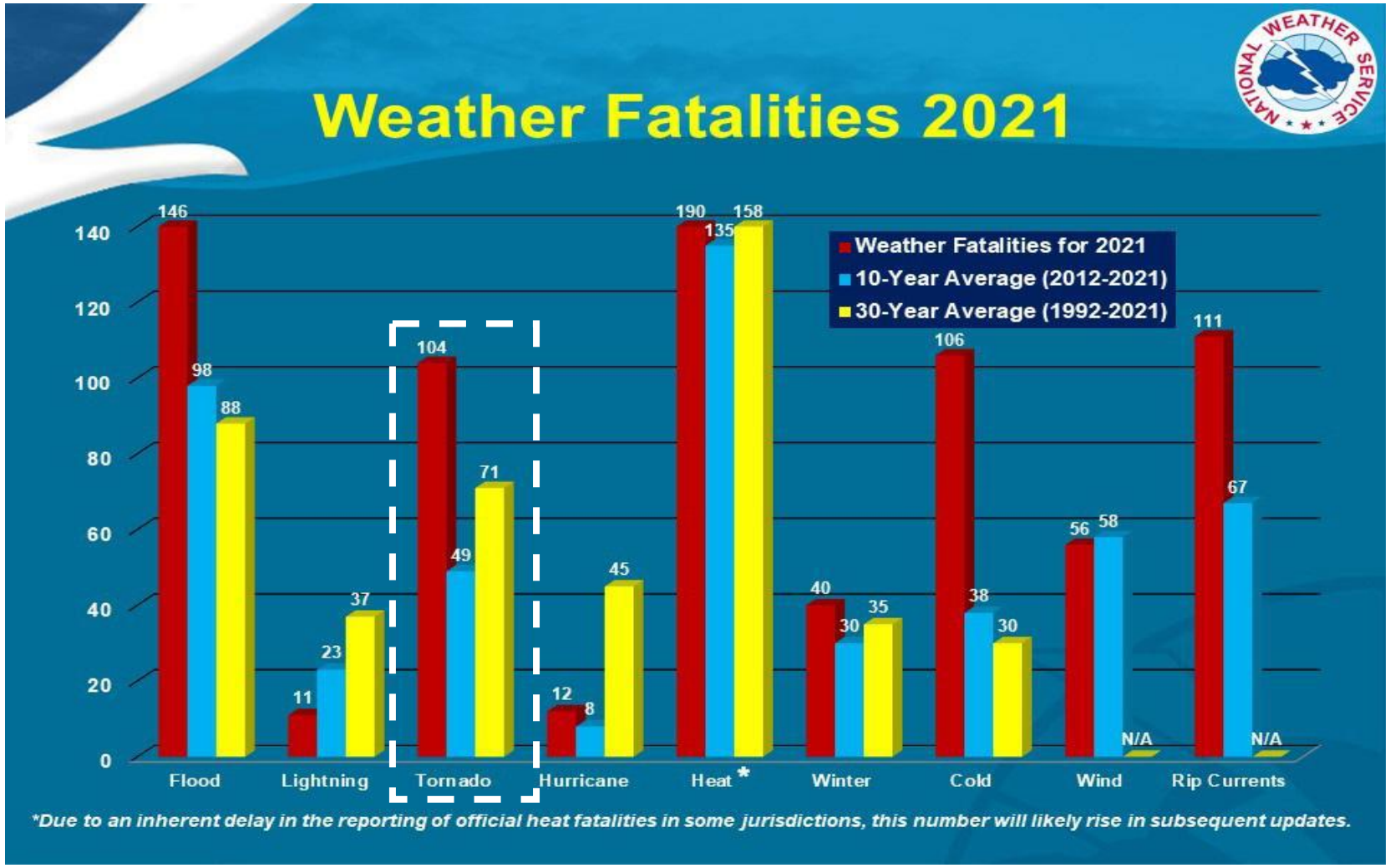
NOAA Weeks 3-4/S2S webinar series
06/March/2023

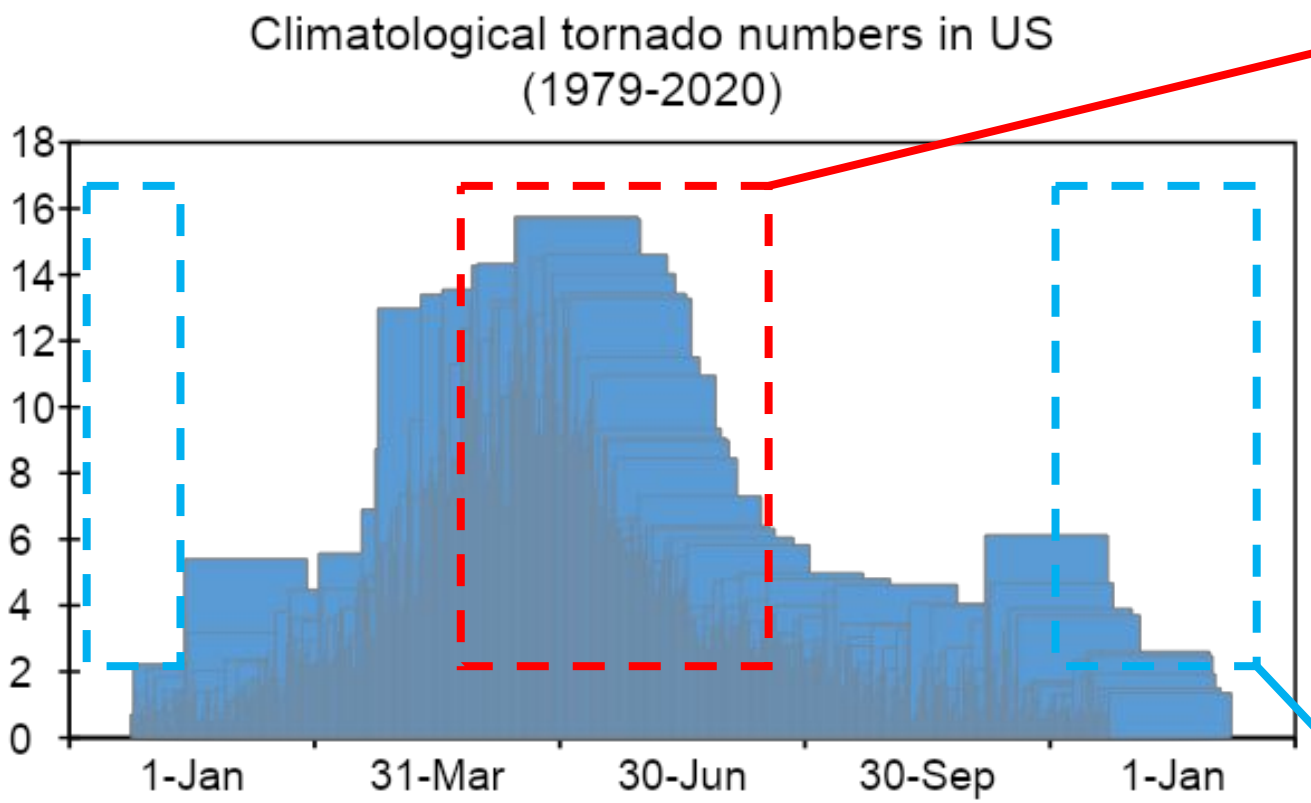
Fatalities by natural extreme weather events

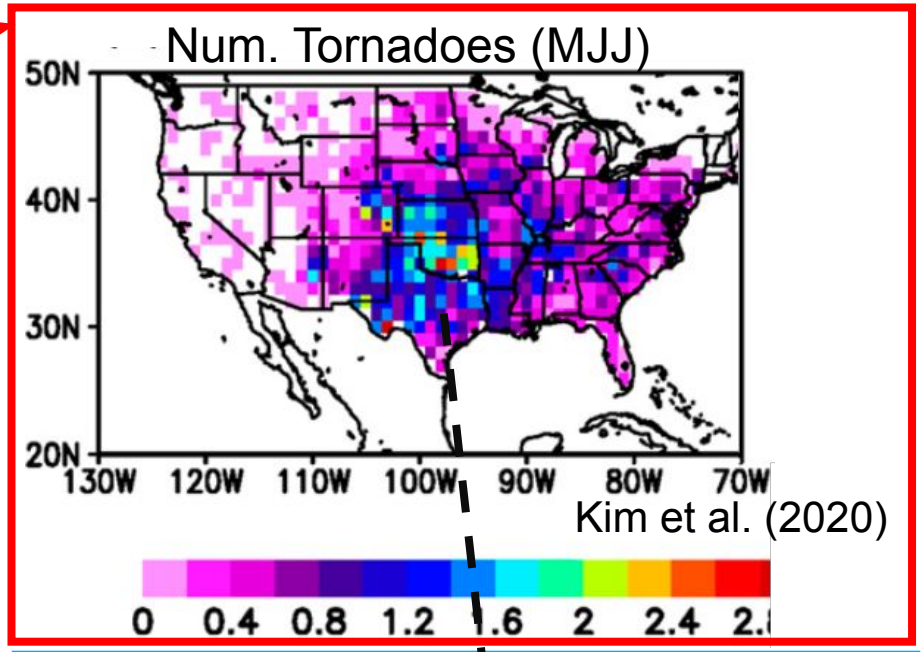
The US Natural Hazard Statistic report (2021)

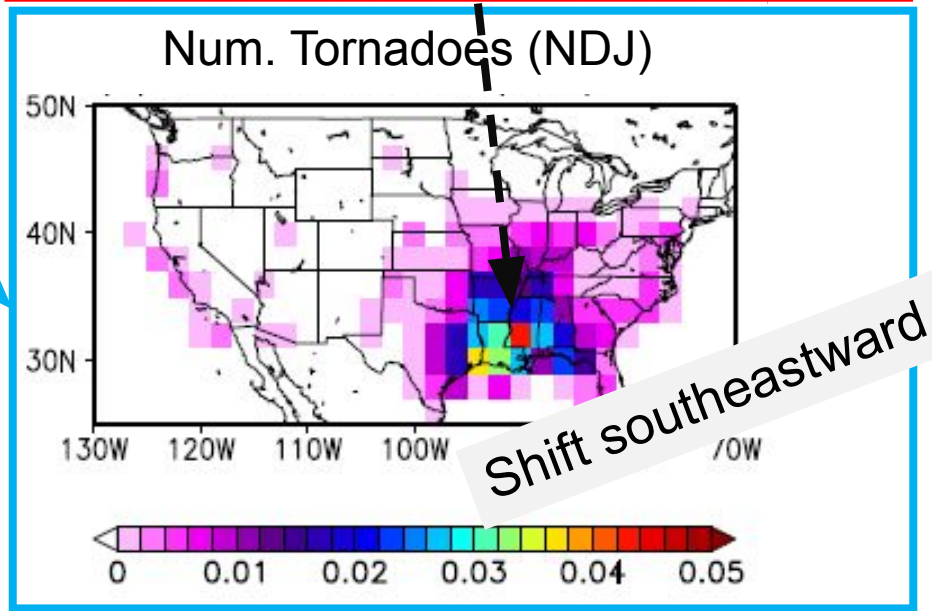


- According to the US Natural Hazard Statistics report, tornado is one of the hazardous weather events (e.g., 71 fatalities in 30-year average)

Climatology of tornadoes



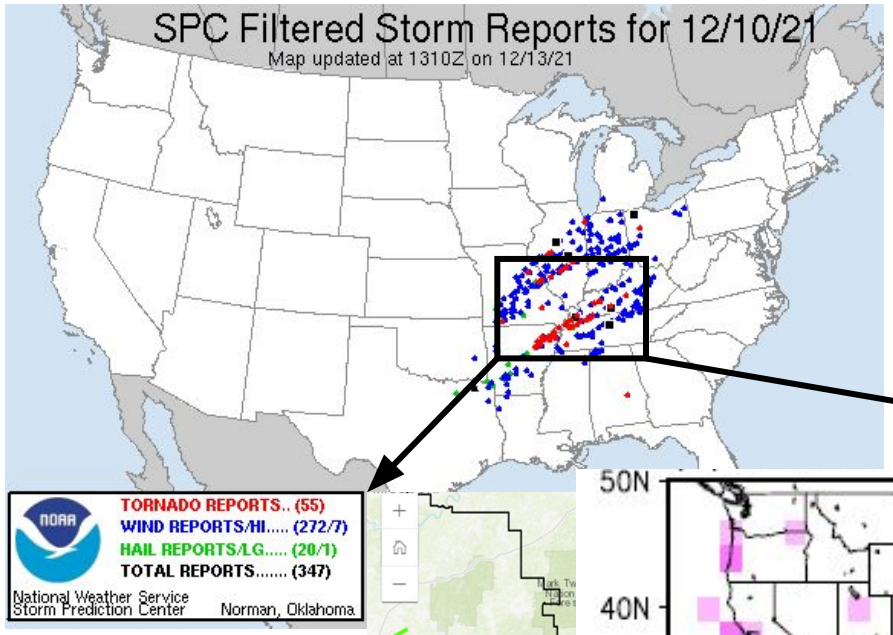




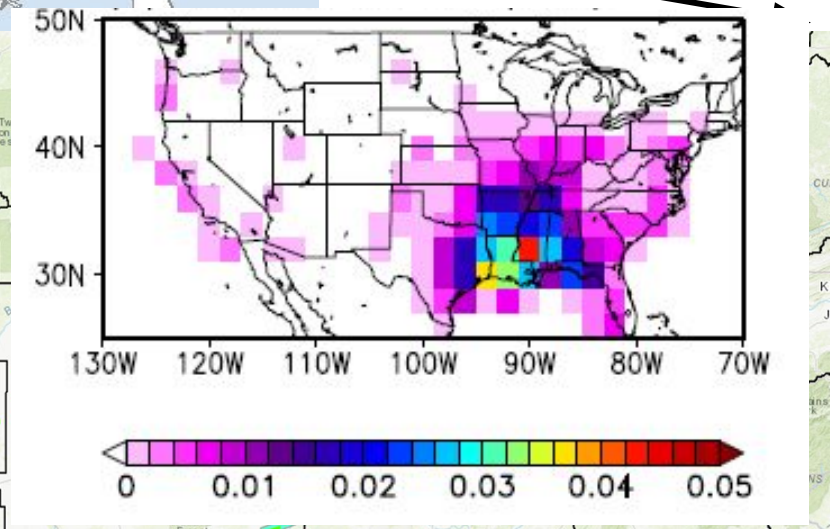
- The occurrence of tornadoes increases sharply in boreal spring and then decreases rapidly after reaching its peak in April, May, and June.
- However, the occurrence of significant tornadoes is not only limited to the boreal warm-season but also to the cold-season.

Quad-states tornado outbreak on 10-11 DEC 2021

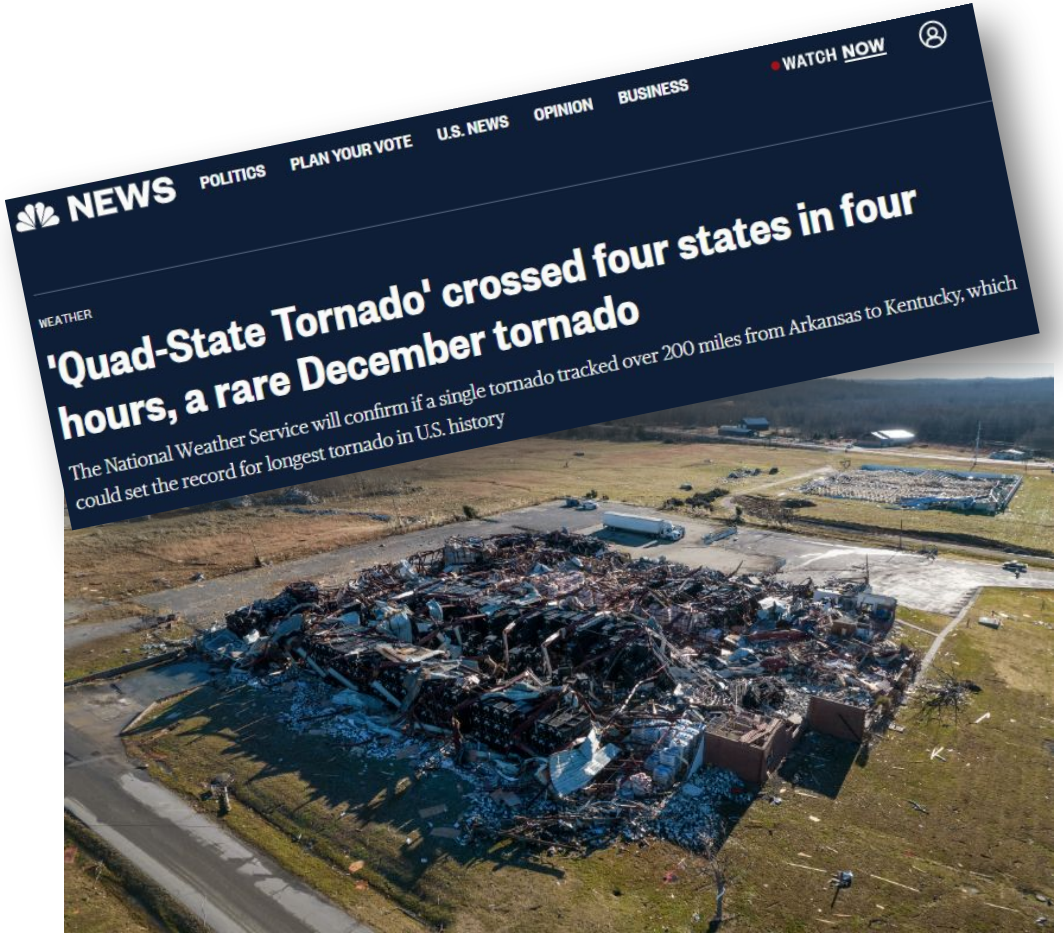
Quad-states tornado outbreak (10-11 December 2021)



Areas occurring the quad-state tornado outbreak were shifted northeastward than the cold-season climatological tornadogenesis



https://www.weather.gov/pah/December-10th-11th-2021-Tornado

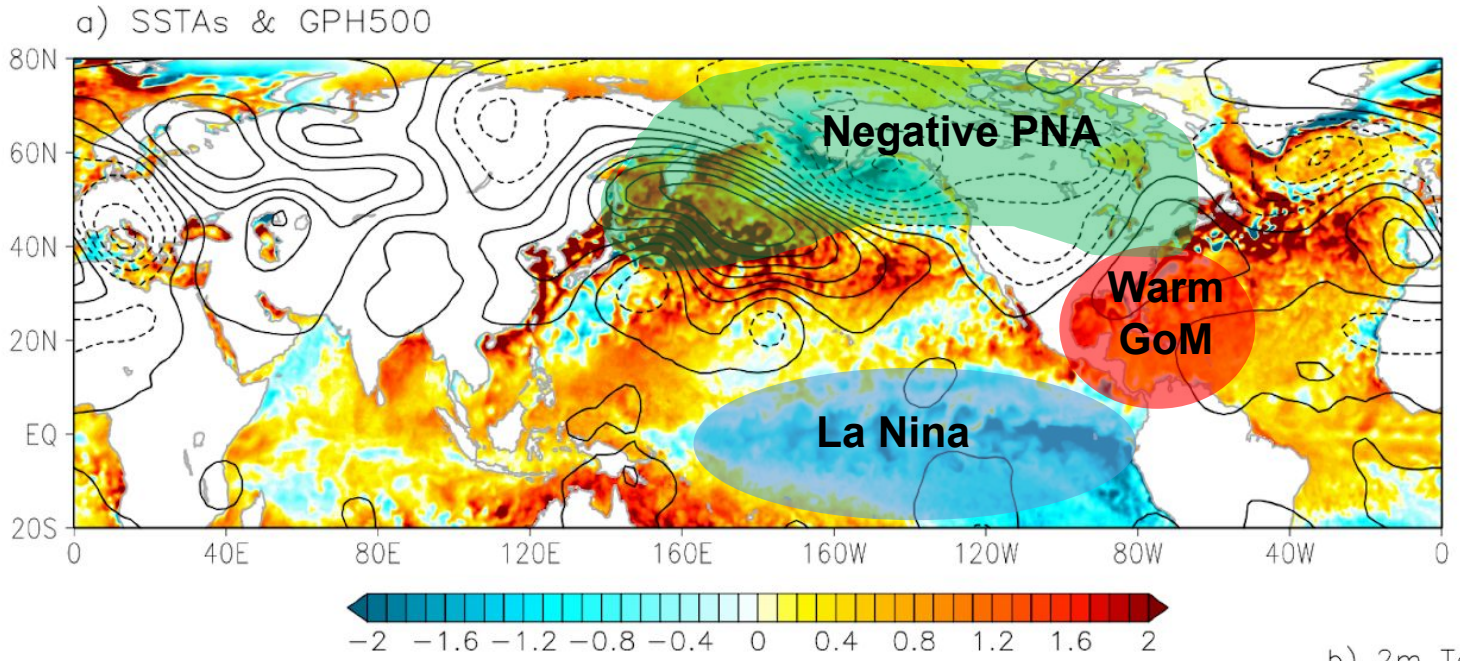


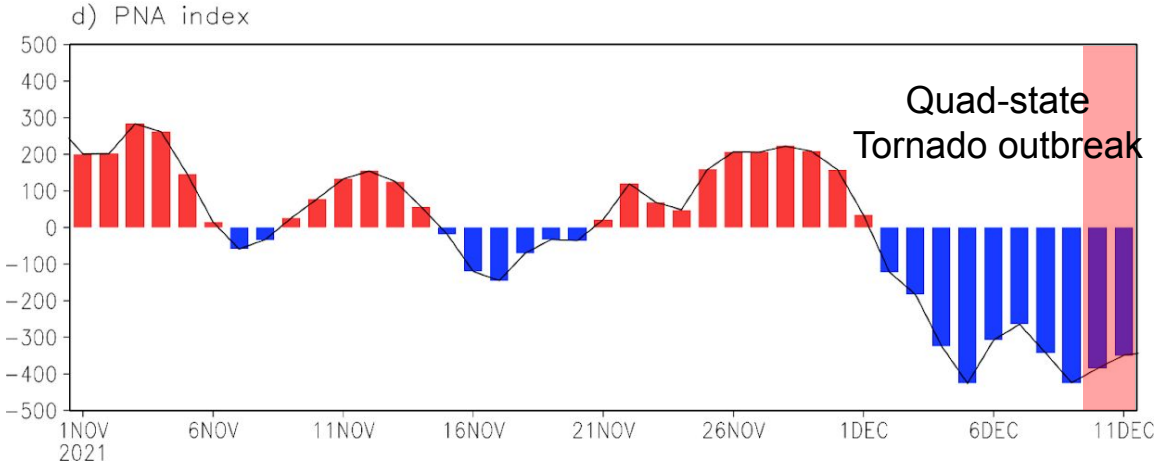
Damage to Factory in Dawson Springs, KY

- Fatalities : 89
- Injuries : 672
- Estimated damage: $3.9 billion

Large-scale environments during the quad-states tornado outbreak

Quad-states tornado outbreak (10-11/DEC/2022)

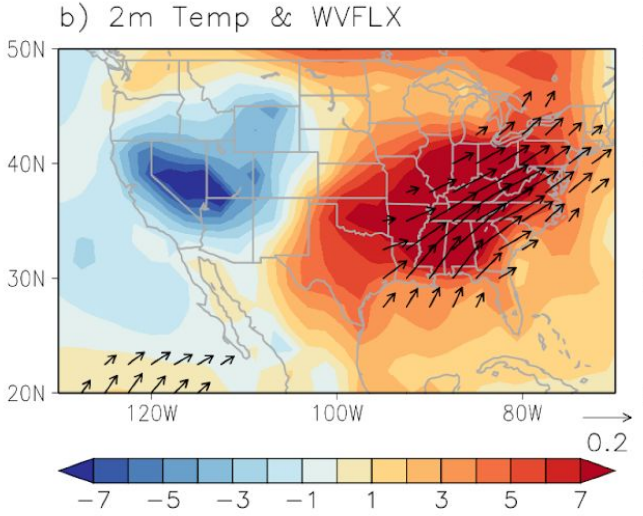




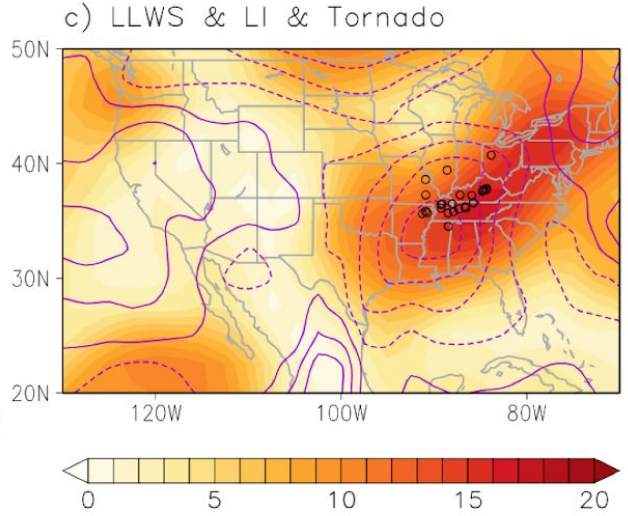
Large-scale environmental conditions

- Negative PNA
- Warm GoM
- La Nina
- Increase in low-level wind shear (LLWS)
- Warm 2m temperature over the eastern U.S.
- Negative lifted index (LI)
- Increase in moisture flux

=> Favorable conditions for tornadoes



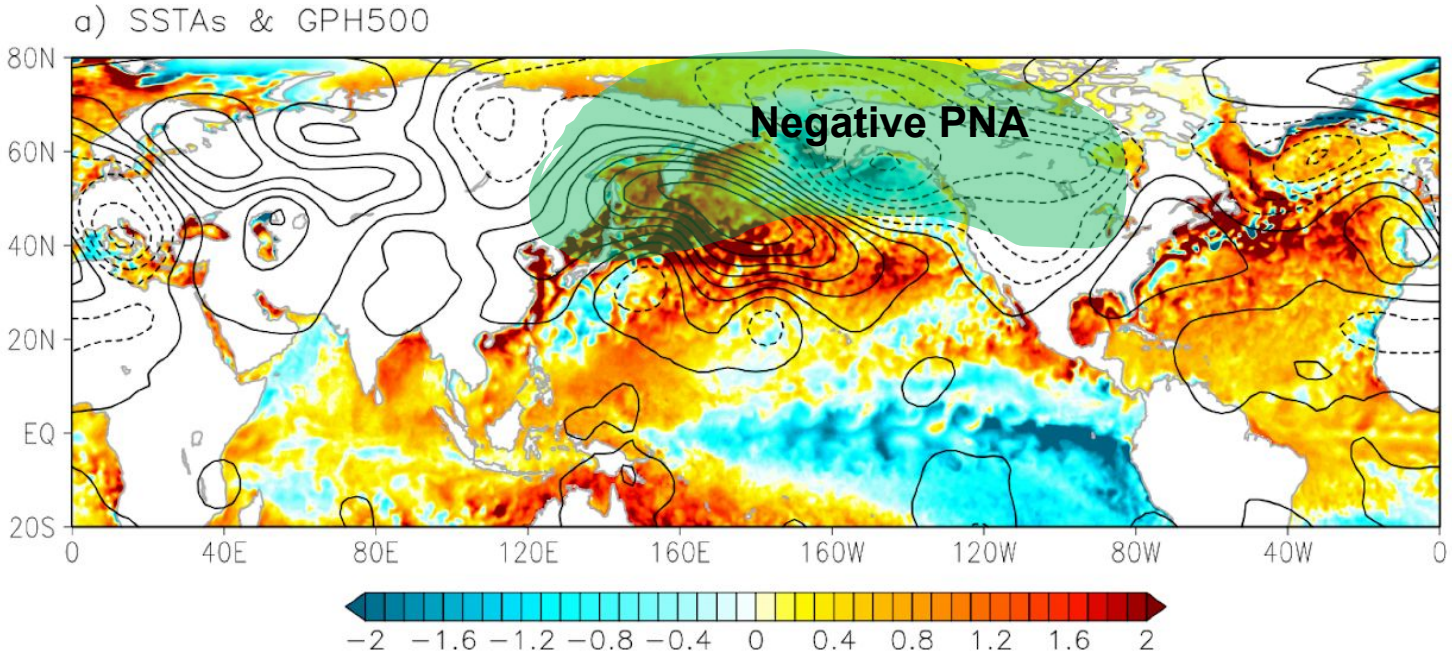
Shading : 2m Temp, Vector: Moist flux:



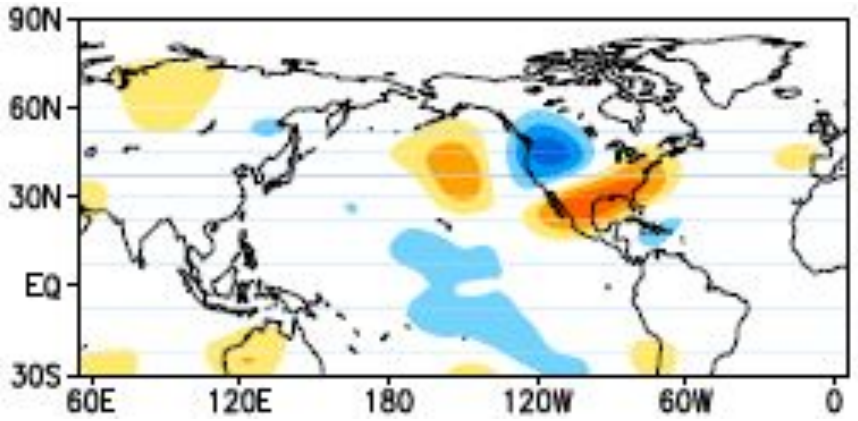
Shading : LLWS, Contour: Lifted Index, Dots: Tornadoes

Links between cold-season tornadoes and climate variability

Quad-states tornado outbreak (10-11/DEC/2022)



Pacific-North America pattern



Corr. Between 200 hPa and 1st SVD mode of local storm reports

Wang et al. (2021)

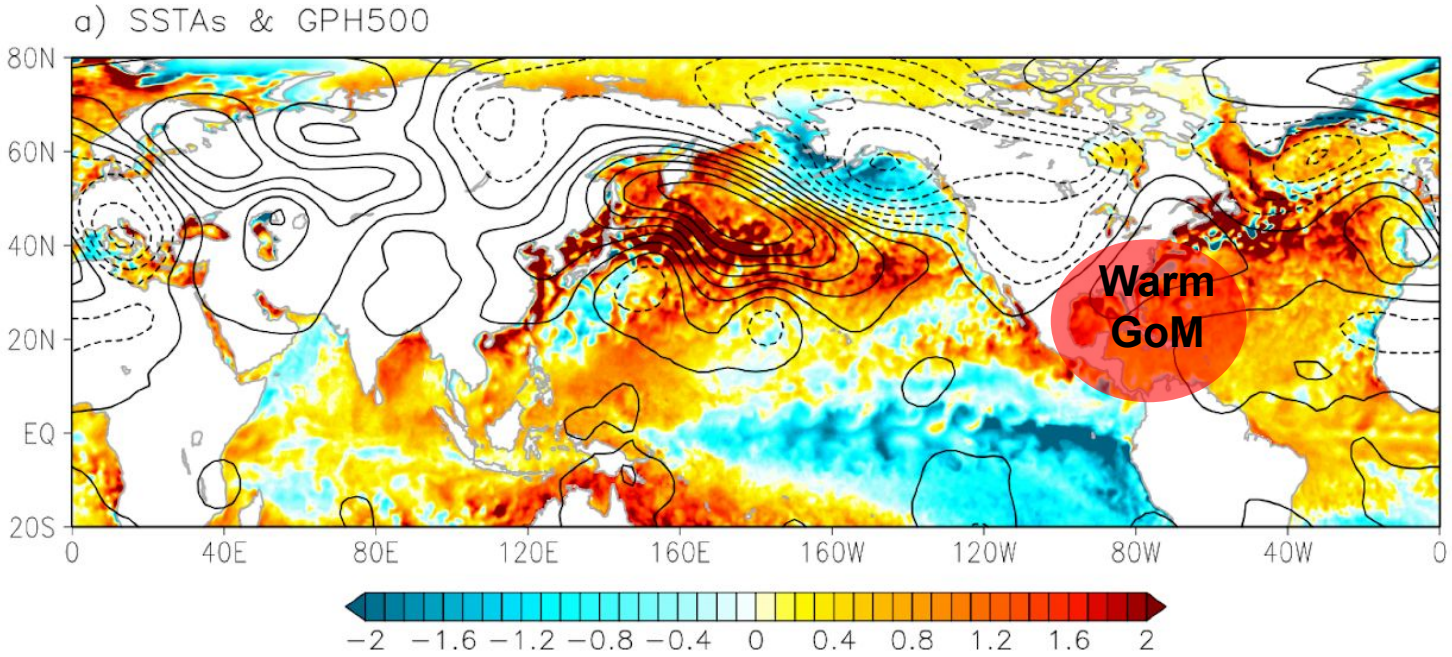
- Favorable conditions for active tornadoes

1. **Negative PNA-liked pattern (e.g., Wang et al., 2021)**
2. Warm GoM SST (e.g., Molina et al., 2018)
3. La Nina condition (e.g., Allen et al., 2015, Lee et al., 2013;2016)

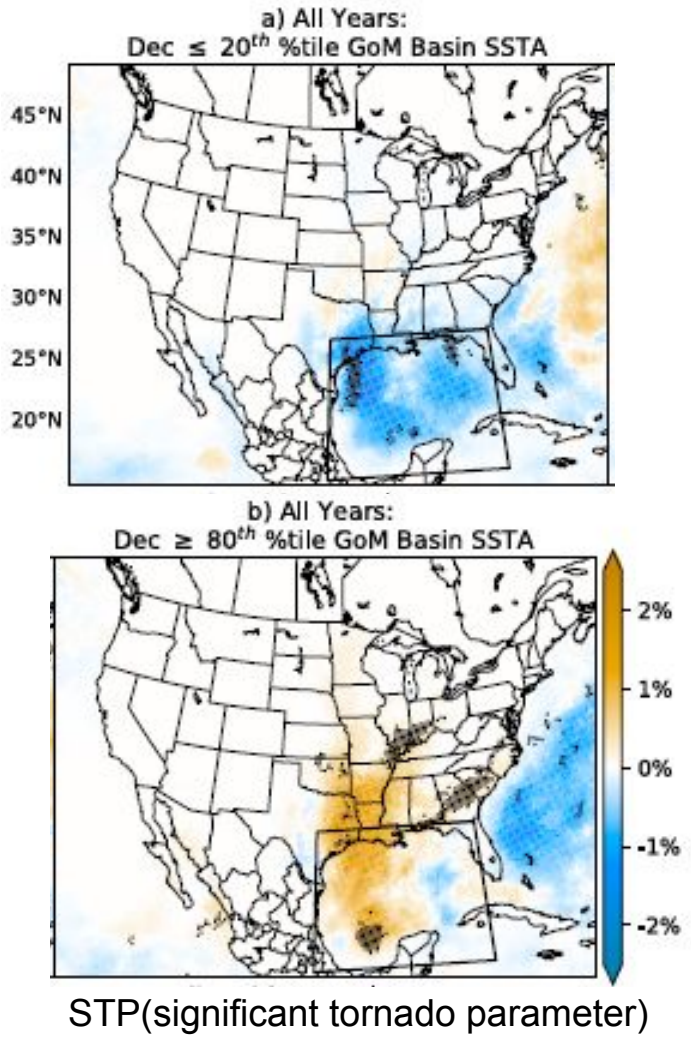
- Negative PNA pattern is a favorable condition for tornado genesis.

Links between cold-season tornadoes and climate variability

Quad-states tornado outbreak (10-11/DEC/2022)



GoM SSTAs



Cold GoM

Warm GoM

STP(significant tornado parameter)

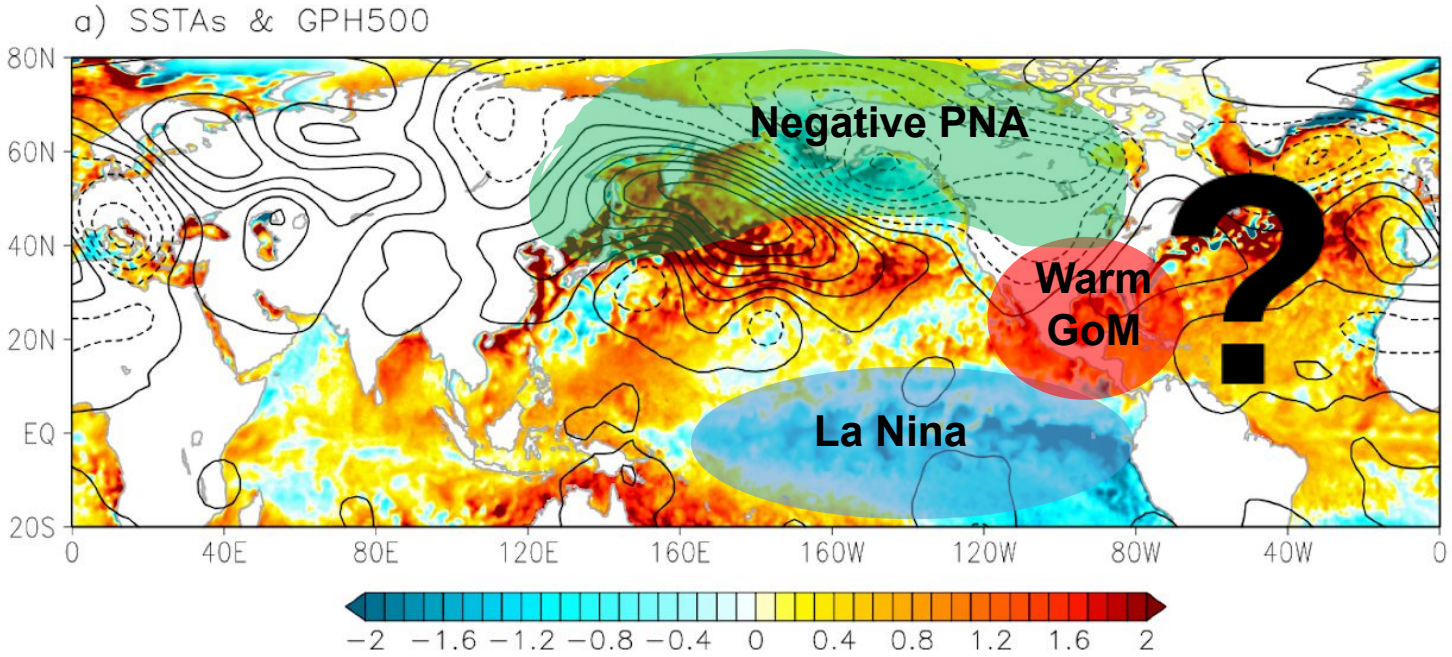
- Favorable conditions for active tornadoes

1. Negative PNA-liked pattern (e.g., Wang et al., 2021)
2. **Warm GoM SST (e.g., Molina et al., 2018)**
3. La Nina condition (e.g., Allen et al., 2015, Lee et al., 2013;2016)

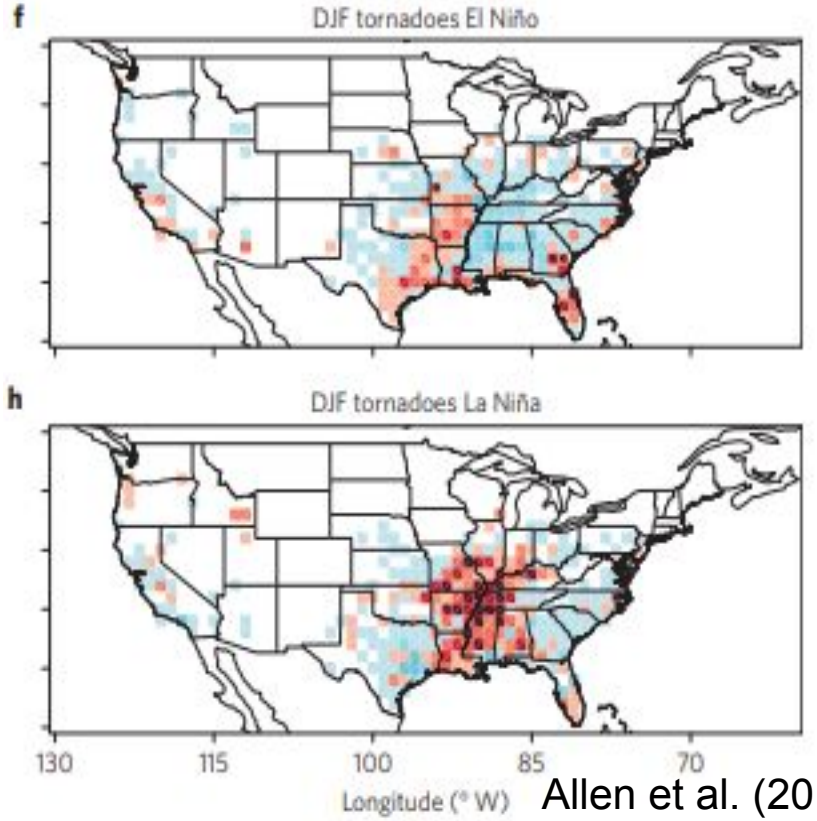
- Warm GoM enhances the probability of a significant tornado environment.

Links between cold-season tornadoes and climate variability

Quad-states tornado outbreak (10-11/DEC/2022)



ENSO



Allen et al. (2015)

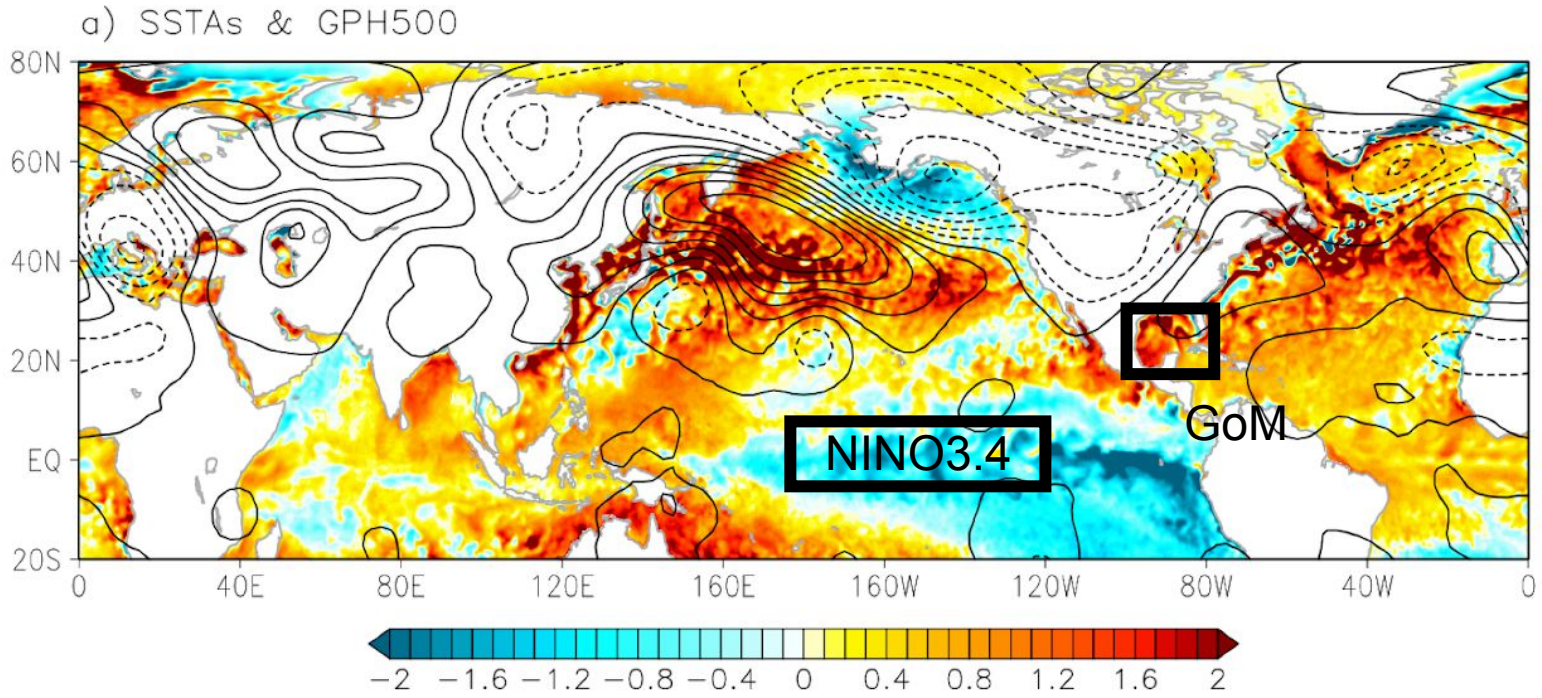
- Favorable conditions for active tornadoes

1. Negative PNA-liked pattern (e.g., Wang et al., 2021)
2. Warm GoM SST (e.g., Molina et al., 2018)
3. **La Nina condition (e.g., Allen et al., 2015, Lee et al., 2013;2016)**

- ENSO modulates tornado and hail occurrence during the boreal winter by altering the large-scale environment.

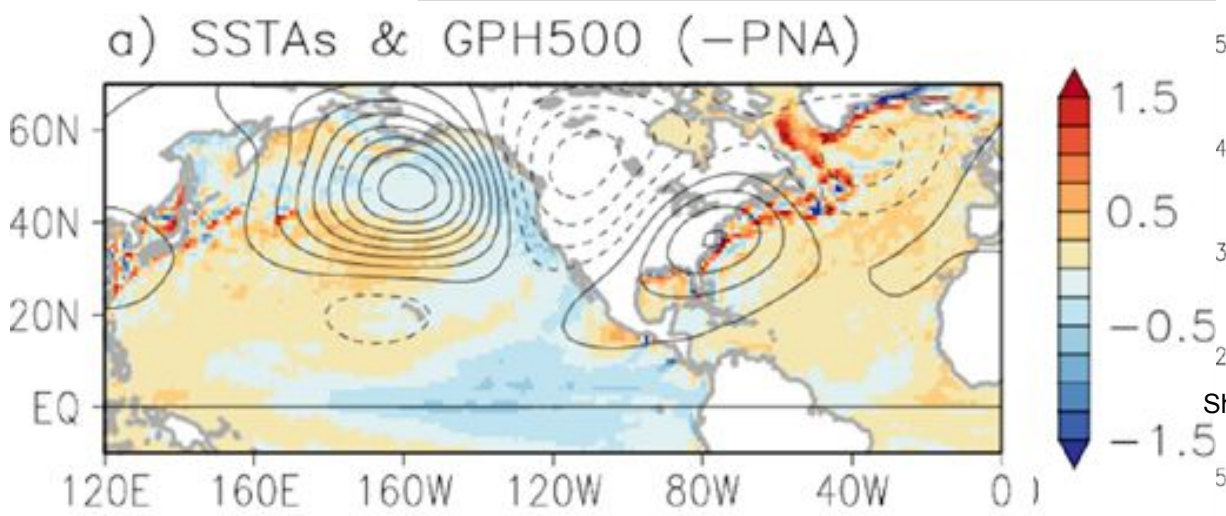
Data and Methods

- Daily SST data : OI SSTv2 daily data
- Daily atmospheric variables : NCEP1 reanalysis and NARR reanalysis
- Daily PNA index: Pattern of GPH at 500 hPa from NOAA PSL
- Tornadoes : EF 1-5 tornadoes from SPC report
- Period: 1982-2021 (40 years), Focused on during NDJ (total n=3680).
- All data are linearly detrended.
- Positive (negative) PNA, Warm (cold) Nino3.4 and GoM are defined by over (less) than 0.5 standard deviations of each index.



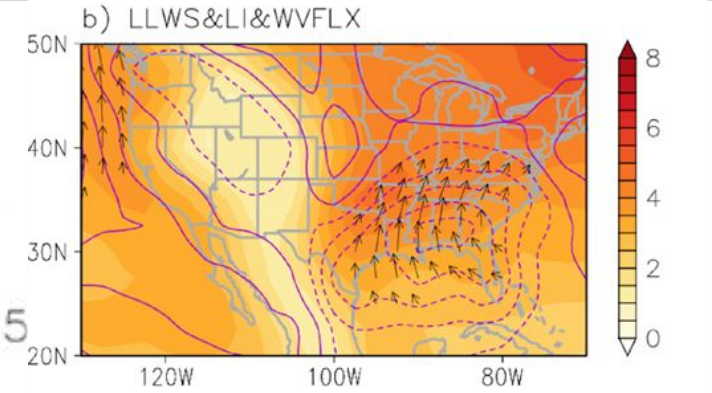
- CESM-LENS : Pre-industrial experiments. (400 years). Focused on during NDJ (total n=36800)

Impacts of negative PNA on cold-season US tornado outbreaks



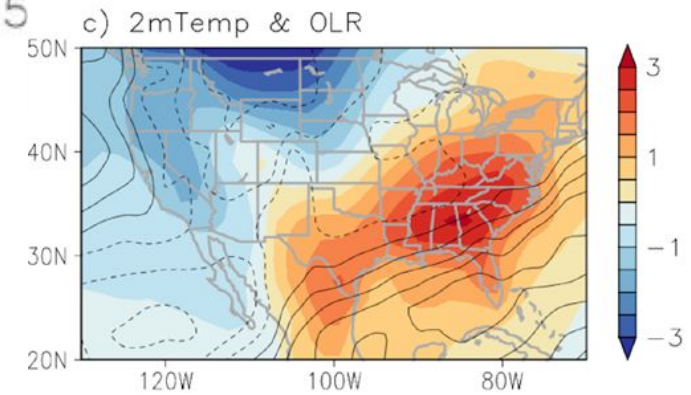
Shading : SSTAs , Contour: GPH at 500 hPa:

- A negative PNA is associated with a strong anomalous atmospheric ridge and trough over the northern Pacific and the Gulf of Alaska, which produces an anomalous anticyclonic circulation centered over the eastern US



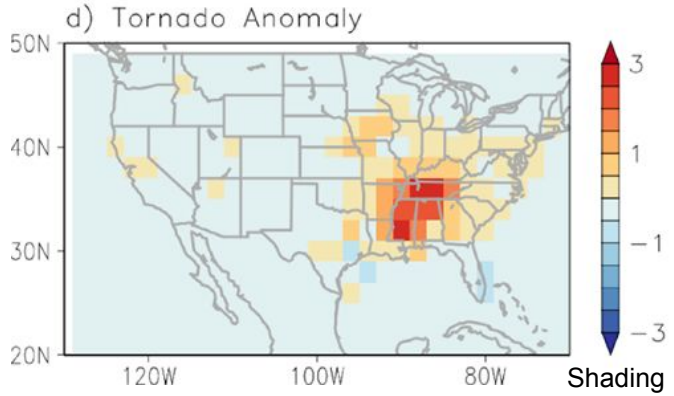
Shading : LLWS , Contour: Lifted index, Vectors: Moist flux

- Enhancement of the North-America low-level jet (NALLJ), the moisture flux and low-level wind share (LLWS) over the southern and eastern US



Shading : 2m temp , Contour: OLR

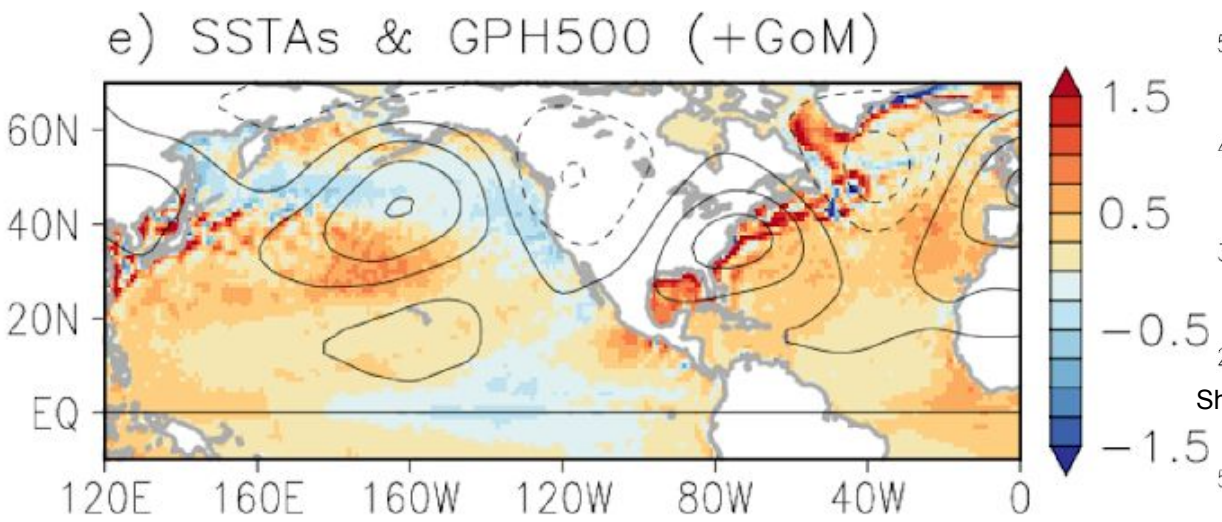
- Positive OLR anomalies along the eastern US seaboard increase incoming shortwave radiation



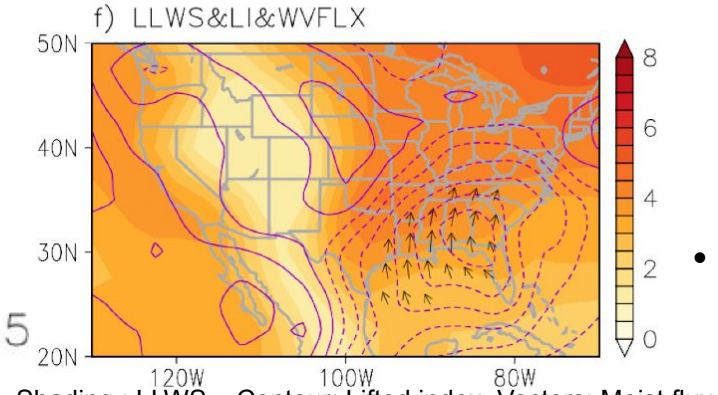
Shading : tornadogenesis

- Tornadogenesis largely increases over the southeast and eastern US.

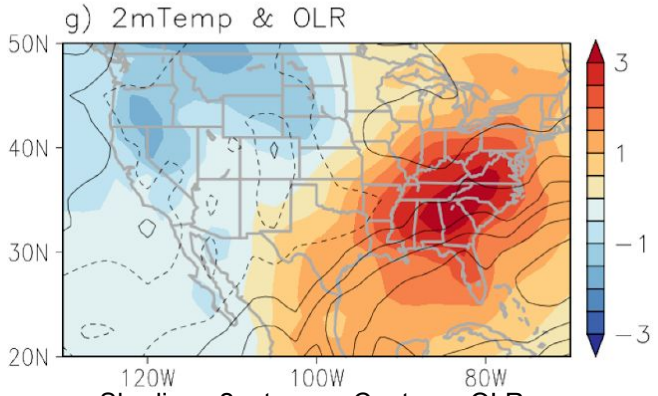
Impacts of warm GoM on cold-season US tornado outbreaks



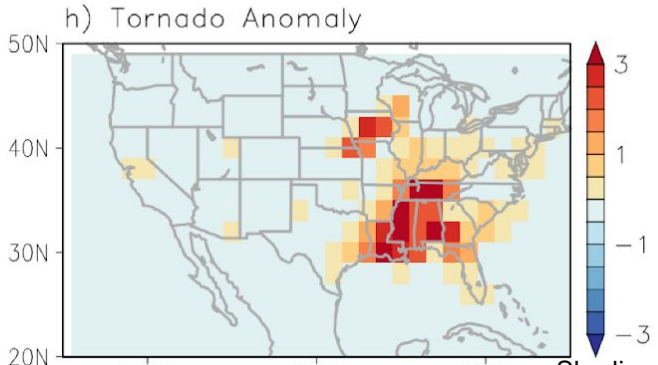
- Consistent with a negative PNA, during warm GoM, Despite having a weaker amplitude compared to the negative PNA, there are a paired atmospheric ridge and trough over the northern Pacific and the Gulf of Alaska, which produces an anomalous anticyclonic circulation centered over the eastern US.



Shading : LLWS , Contour: Lifted index, Vectors: Moist flux



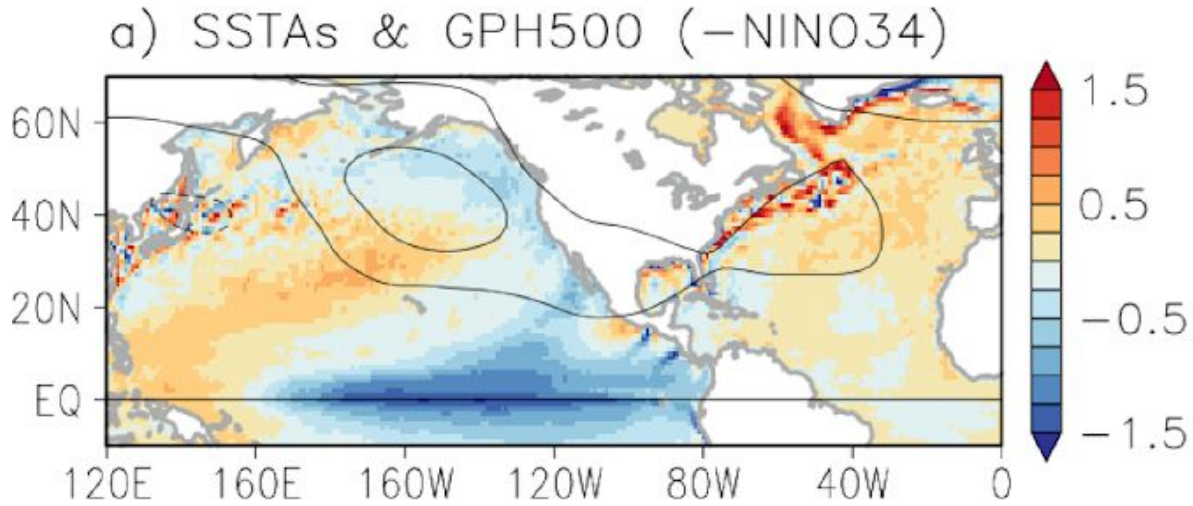
Shading : 2m temp , Contour: OLR



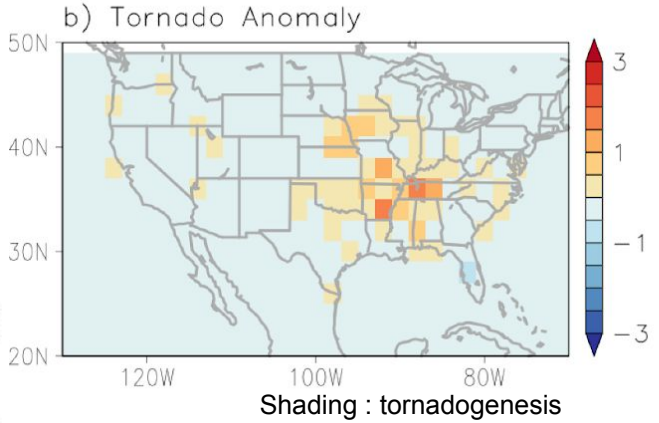
Shading : tornadogenesis

- The spatial pattern of near-surface temperature, OLR anomalies, and other tornadic environments are highly consistent with those during negative PNA.
- As result in, the tornado activity also increases during warm GoM.

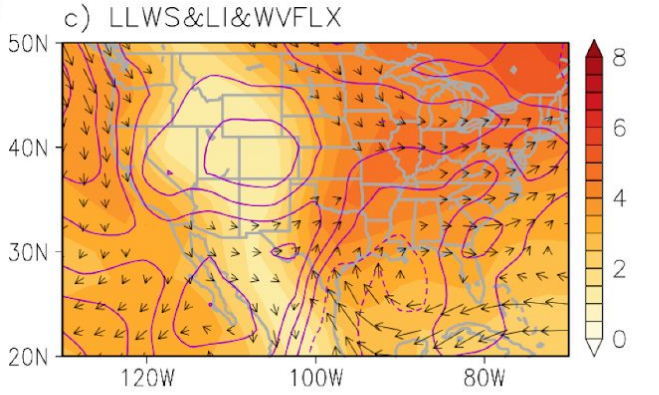
Impacts of La Nina on cold-season US tornado outbreaks



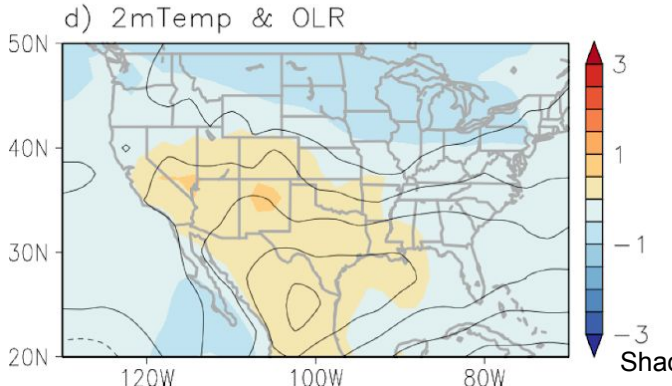
- The anomalous atmospheric ridge centered in the North Pacific stretches out to the southern US.



Shading : tornadogenesis



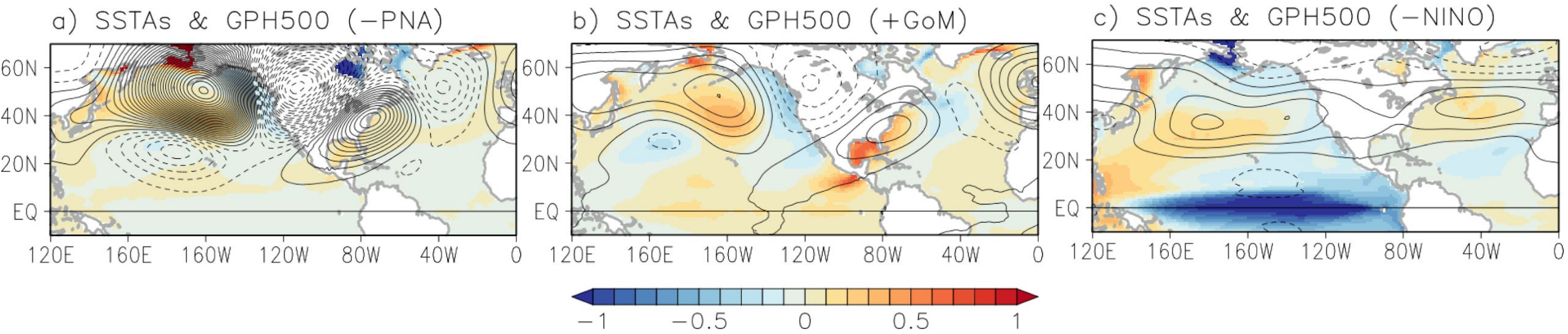
Shading : 2m temp , Contour: OLR



Shading : LLWS , Contour: Lifted index, Vectors: Moist flux

- During La Niña, the cold-season US tornado activity increases. However, it is weaker compared to that during negative PNA and warm GoM
- The spatial patterns of environmental conditions are different from those during negative PNA and warm GoM.
- These results clearly illustrate that the La Niña condition is not a necessary component to generate a negative PNA-like pattern, a major contributor to an increase in the cold-season US tornado outbreak (e.g., Dai et al., 2017; Lopez., 2018; Li et al., 2019).

Climate variabilities (CESM-LENS)

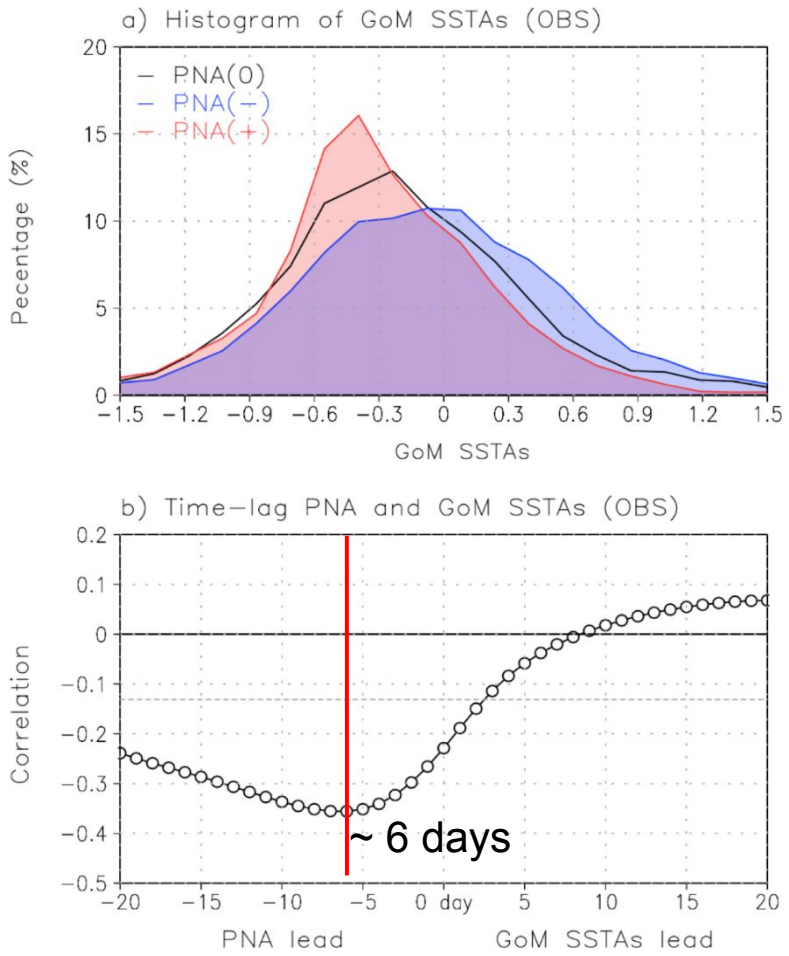


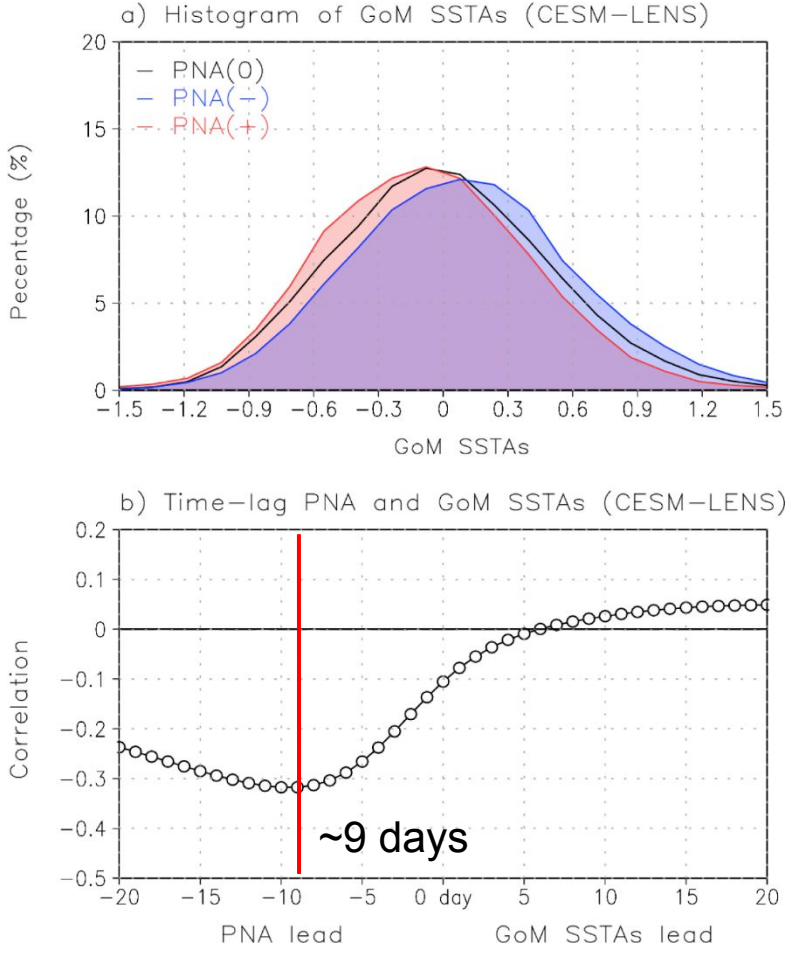
- The spatial patterns of SSTAs and geopotential height at 500 hPa derived from CESM-LENS highly consistent with the results from observations and reanalysis datasets

  - High consistency of spatial pattern of GPH500 between a negative PNA and warm GoM SSTAs

  - Elongation of atmospheric ridge located in the North Pacific toward the southern US during La Nina

Relationship between negative PNA and warm GoM SSTAs





- To support this hypothesis, the results derived from CESM-LENS are highly consistent with those from observation and reanalysis datasets

- During the negative PNA, the occurrence of warm GoM SSTAs is more frequent than that during neutral and positive PNA phases.

- The lead-lag correlation indicates that a negative PNA phase leads the warm GoM SSTAs with a lag of approximately six days whereas a positive PNA leading the cold GoM SSTAs is not statistically significant.

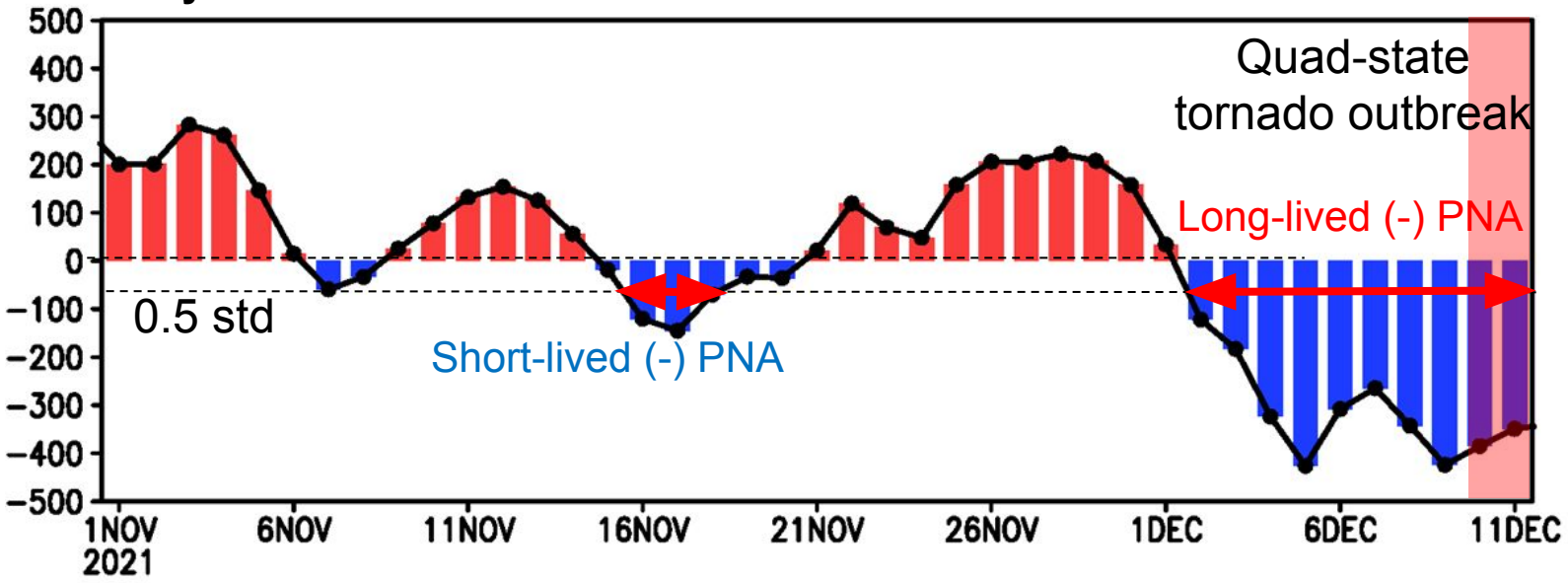
Hypothesis of the quad-state tornado outbreak

A hypothesis:

- A persistent negative PNA can generate a blocking high over the eastern U.S., which in turn leads to the northward shifted jet stream and a clear sky.

- Therefore, the persistent negative PNA can increase GoM SSTAs and near-surface temperature over the eastern U.S., enhancing moisture flux from the GoM to eastern U.S. and increasing instability over the eastern U.S., which are favorable conditions for generating tornadoes across the Mississippi Valley and Ohio Valley.

Daily PNA index

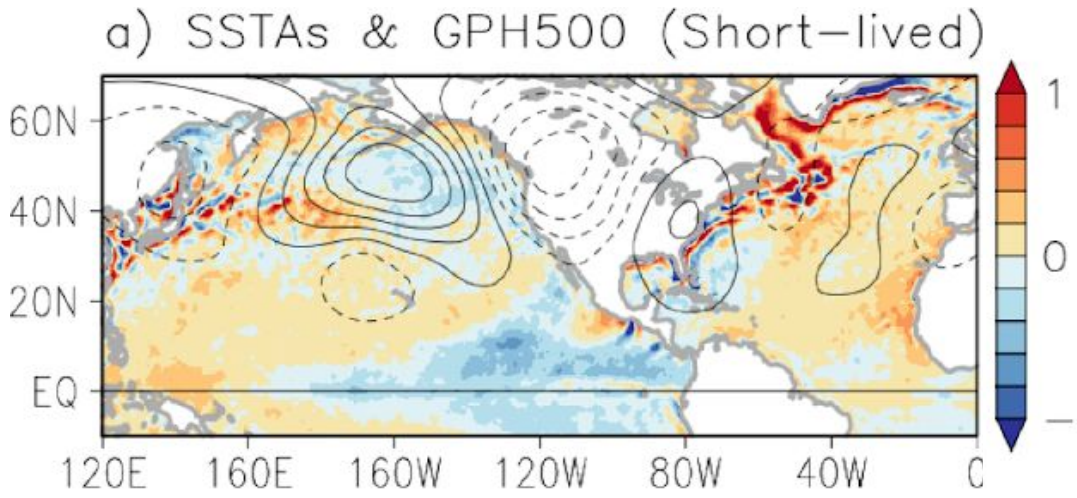


- To examine this hypothesis, we separated two negative PNA cases.

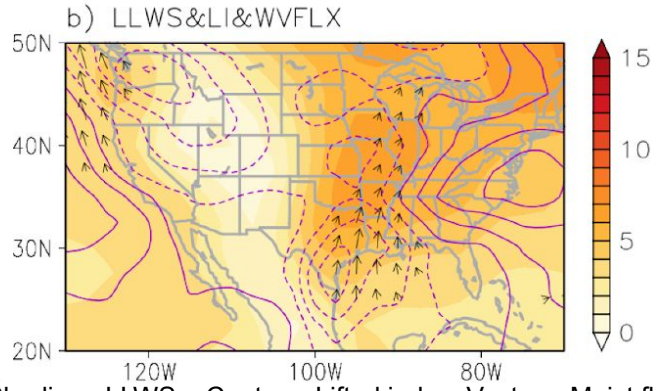
- Short-lived negative PNA case: The negative PNA (less -0.5 std) persists for less than for 6 days.

- Long-lived PNA negative case: The negative PNA (less -0.5 std) persists for equal to or more than for 6 days.

Short-lived negative PNA: Its link to cold-season US tornado outbreak

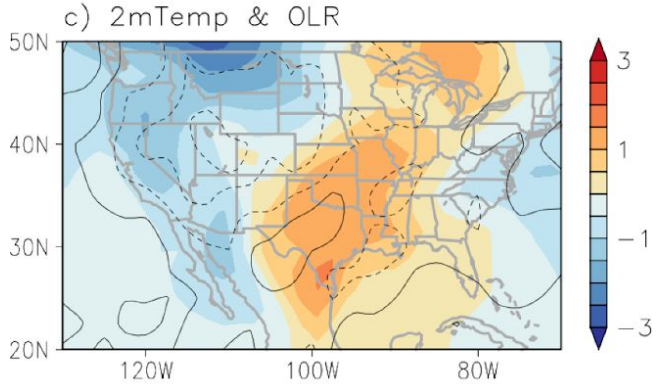


- A paired anomalous ridge and trough appears over the North Pacific and the Gulf of Alaska.
- The anomalous ridge extends meridionally over the eastern US, producing low-level southerly moisture flux anomalies over the central US.



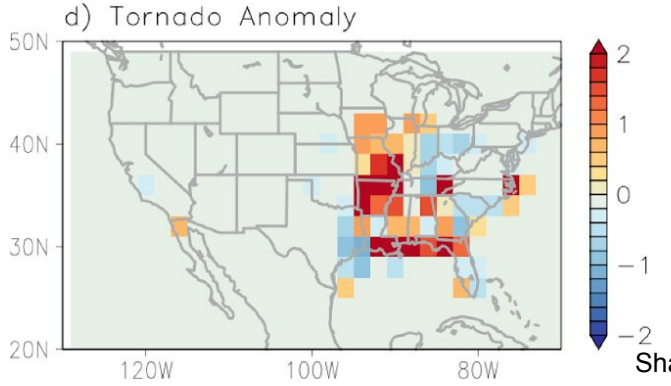
Shading : LLWS , Contour: Lifted index, Vectors: Moist flux

- Increased LLWS, moisture flux and decreased LI over the central US, which are favorable conditions for tornadogenesis



Shading : 2m temp , Contour: OLR

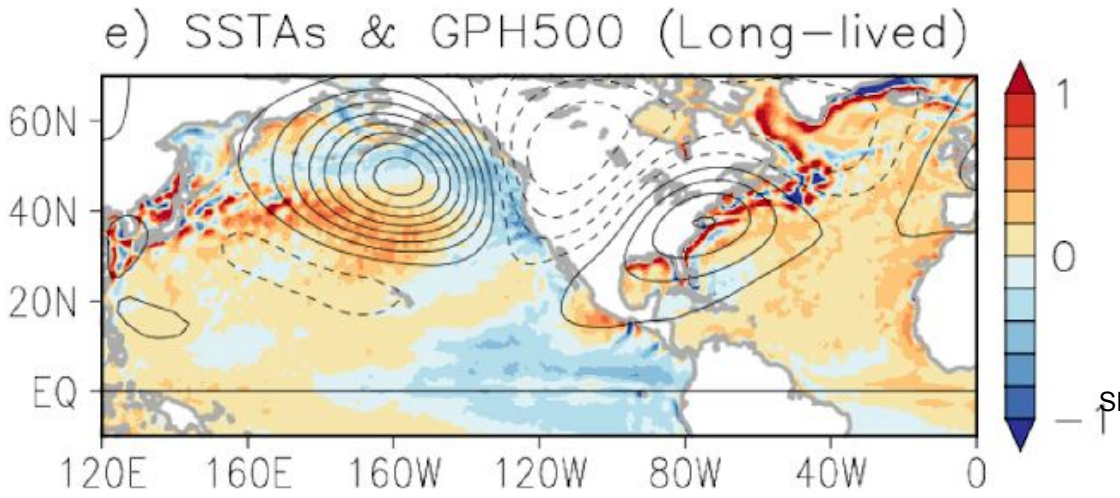
- The near-surface temperature is warm over the central US



Shading : tornadogenesis

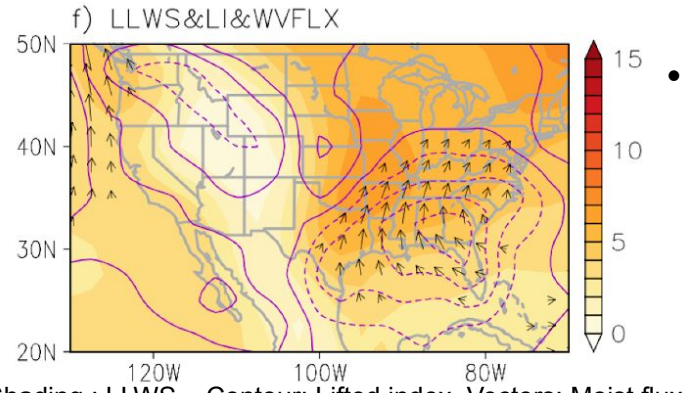
- Tornadogenesis is likely to occur in the central US

Long-lived negative PNA: Its link to cold-season US tornado outbreak

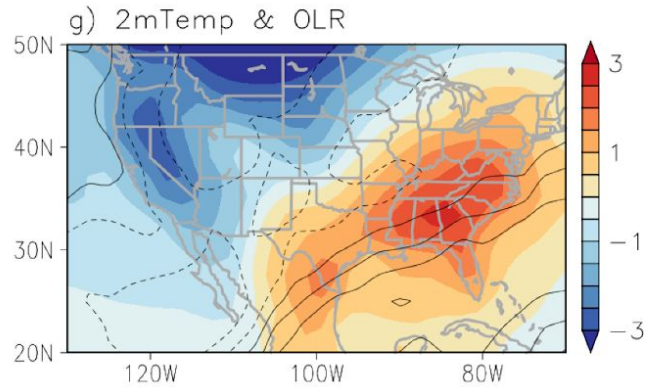


- Consistent with the short-lived negative PNA, a paired atmospheric ridge and trough appears over the North Pacific and the Gulf of Alaska.

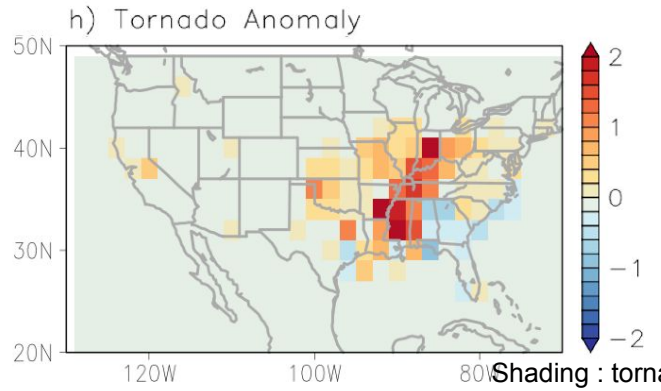
- This anomalous ridge lies along the eastern US seaboard, which is similar to the quad-state tornado outbreak.



Shading : LLWS , Contour: Lifted index, Vectors: Moist flux



Shading : 2m temp , Contour: OLR



Shading : tornadogenesis

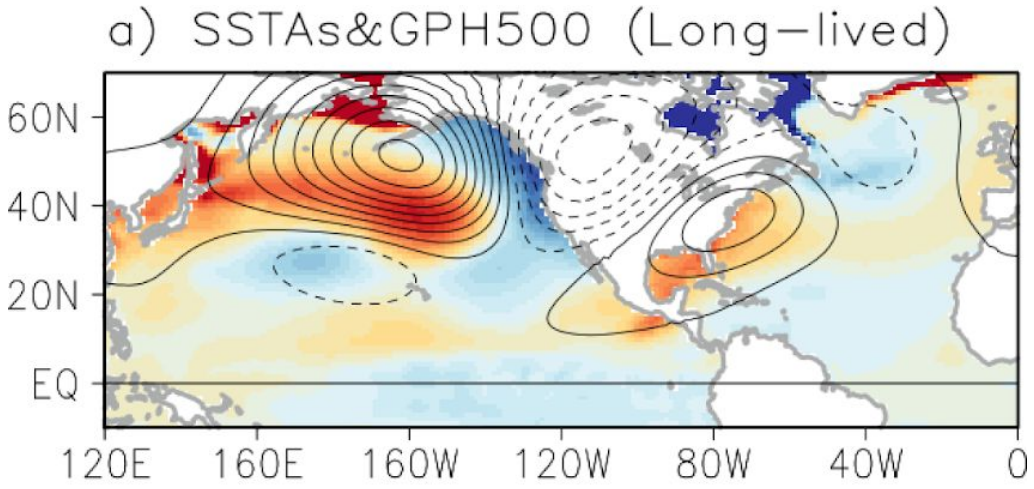
- Increased low-level southwesterly anomalies over the central and eastern US, thus increasing atmospheric instability (i.e., LLWS and LI), and extending NALLJ toward the central and eastern US

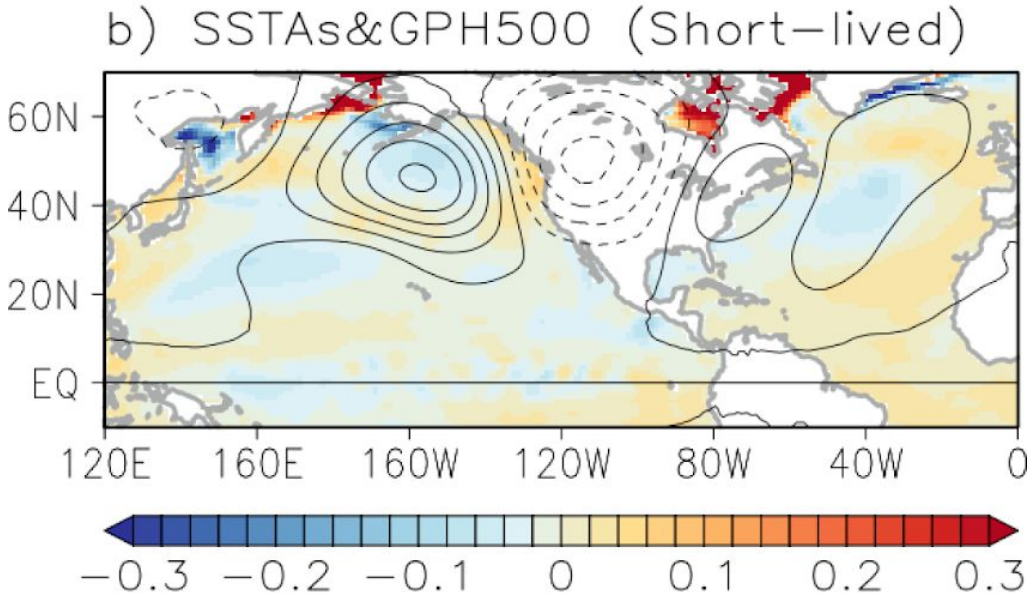
- Anomalous ridge along the eastern US seaboard produces a strong positive OLR anomaly over the GoM and the eastern US seaboard, increasing GoM SSTAs.

- As a result of this, tornadogenesis shifts eastward during the long-lived negative PNA compared to that during the short-lived negative PNA

- This pattern is highly consistent with the quad-state tornado outbreak.

Long-lived vs short-lived negative PNA (CESM-LENS)





- The results in the spatial pattern of SSTAs and geopotential height at 500 hPa derived from CESM-LENS strongly support our hypothesis

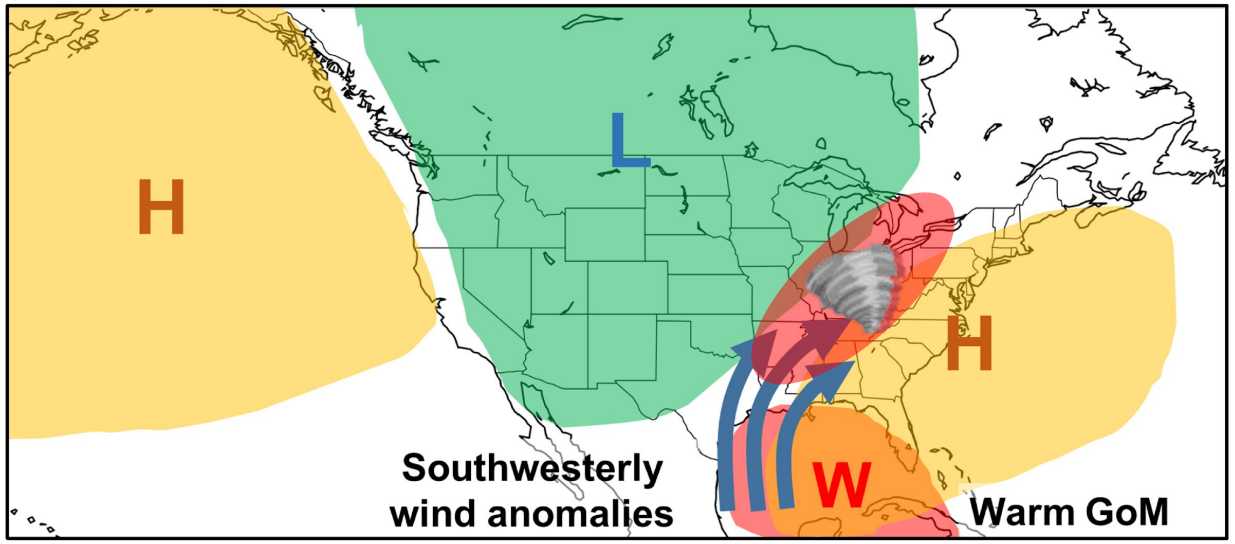
- Short-lived negative PNA :The anomalous ridge extends meridionally over the eastern US.

- Long-lived negative PNA : The anomalous ridge lies along the eastern US seaboard, which is similar to the quad-state tornado outbreak.

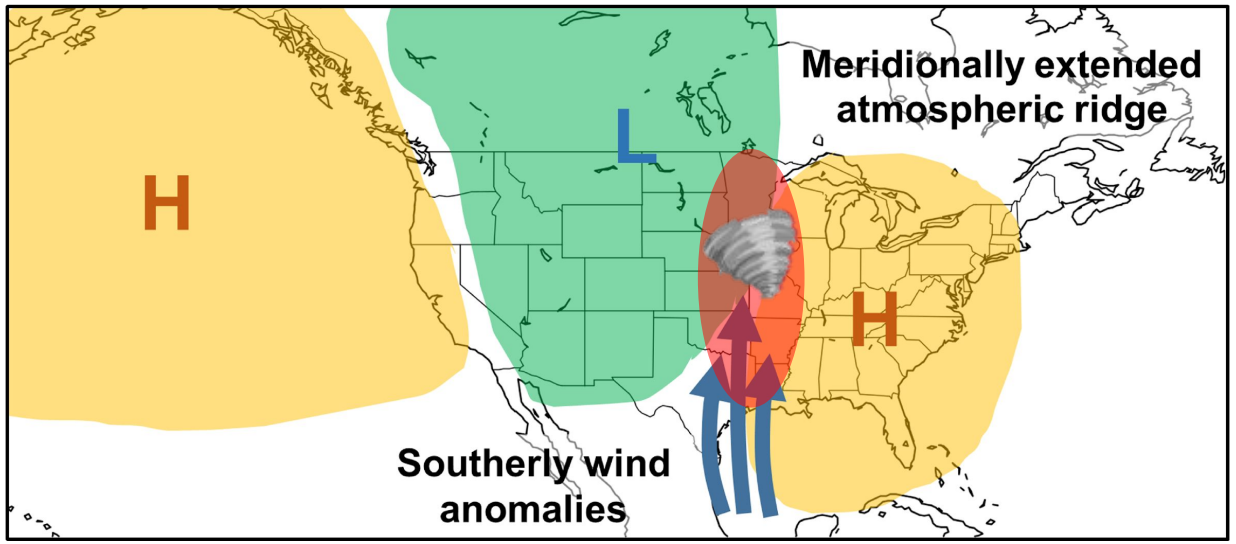
- ***These results suggests that a persistent negative PNA and associated warm GoM are a crucial key for generating the quad-state tornado outbreak.***

Summary

a) Negative PNA persists for longer than 6 days (i.e., Long-lived negative PNA)



b) Negative PNA persists for less than 6 days (i.e., Short-lived negative PNA)



- This study explores the physical links between climate variability and the US quad-state tornado outbreak on December 10-11, 2021.
- The long-lived negative PNA and associated warm GoM SSTAs are closely linked to the cold-season US tornado outbreak across Ohio Valley such as the quad-state tornado outbreak.
- An atmospheric ridge along the eastern US seaboard forced by the long-lived negative PNA increases GoM SSTAs and the NALLJ, increasing atmospheric instability and tornado activity across Ohio Valley.

Thank you for your attention

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