State of the Science FACT SHEET

Tornadoes, Climate Variability, and Climate Change

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION • UNITED STATES DEPARTMENT OF COMMERCE

Scientists and communication experts from the National Oceanic and Atmospheric Administration (NOAA) developed this assessment of tornado activity and climate.

Tornadoes are intense rotating vertical columns of air that pose a great threat to lives and property. They typically form in an environment where winds are rapidly changing direction and speed with height (referred to as wind shear) and the atmosphere is unstable. Tornado damage has historically been classified according to the Fujita (F) scale, with F0 causing the least amount of damage and F5 the most. In 2007, the F-scale was replaced by the Enhanced Fujita (EF) scale, with tornado rating assigned similar EF0–5 designations as the F-scale. While tornadoes can occur during any season in the U.S., they are most frequent during the spring months of April, May, and June.

Given the right set of atmospheric conditions, tornadoes can occur almost anywhere. In fact, tornadoes have been documented on every continent except Antarctica. The United States, by far, has the most frequent and strongest tornadoes in the world. This is related to its unique geography (Rocky Mountains and proximity to the Gulf of Mexico), which contribute to the development of large-scale weather systems capable of supporting severe thunderstorms and tornadoes. The areas of the U.S. most susceptible include the Great Plains, Midwest, and South.

Are the frequency and/or intensity of tornadoes increasing?

Tornadoes can have a significant socioeconomic impact and increasing exposure to tornado risk from increasing urbanization makes the assessment and prediction of changes in tornado frequency, intensity, and seasonality important. Underpinning our current understanding of tornado activity is a long-term (1954–present) record of historical tornado counts from NOAA's Severe Events Database (SED). Given that the SED was not intended to be a consistent, homogenous, long term, definitive record of tornadoes, there are inconsistencies over time as a result of changes in population, public awareness, tornado reporting practices, Doppler radar technology, and National Weather Service (NWS) guidelines, to name a few.

These inconsistencies have likely introduced artificial trends in the tornado record making attribution of long-term changes in tornado climatology difficult to determine[2,3,4]. This issue is highlighted by a comparison of all tornado counts (F/EF0–5) with only the F/EF1–5 tornadoes (Figure 1). Removing the F/EF0 counts from the database nearly eliminates the annual frequency trend, though seasonal trends still exist (not shown). Despite the potential for spurious trends in the SED, this does not rule out the possibility that a portion of the trend is due to climate change or climate variability.

Even though the annual total of F/EF1–5 tornadoes has little to no trend over the record, there has been a large decrease in the

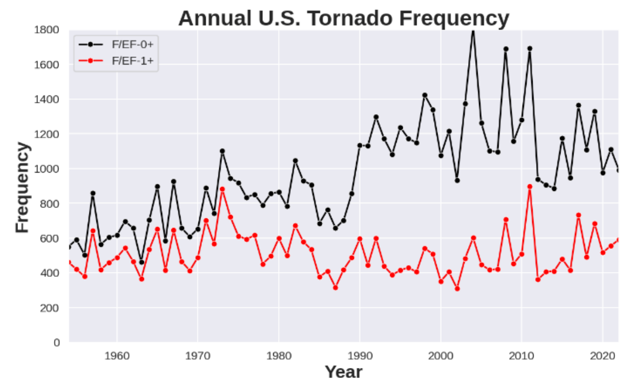

Figure 1: The total annual *number of tornadoes reported* (black) *and number of F/EF1 or stronger tornadoes reported* (*red*).

number of days per year with at least 1 F/EF1–5 tornado since the 1970s, along with a large increase in the number of days per year with numerous (30+) F/EF1–5 tornadoes beginning in the 1990s[1] (Figure 2). However, this trend coincides with the deployment of the WSR-88D Doppler RADAR network, which likely has played a role in increasing tornado detection. no statistically significant trends exist over the most recent 30-year period from 1992–2022. Explaining changes in tornado activity remains an area of active research.

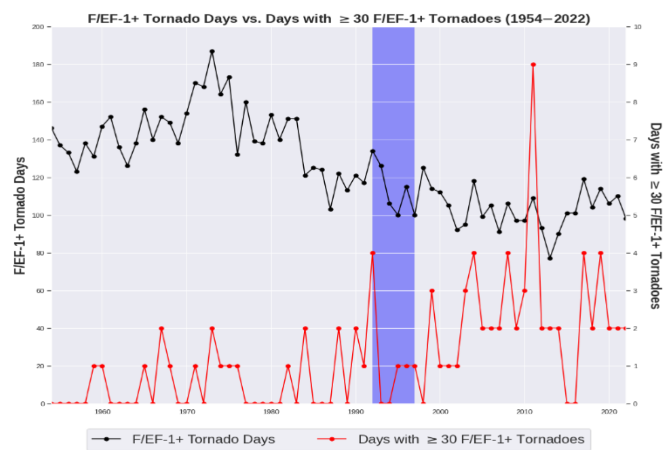

Figure 2: The number of days per year with at least 1 F/EF1 or stronger tornado in the US (black) and number of days per year with at least 30 F/EF1 or stronger (red) for the period. 1954–2022. The blue shading indicates the 5-year implementation period (1992–1997) of the WSR-88D RADAR network. Figure adapted from Brooks et al. (2014).

What is the role of natural climate variability in tornado activity?

Studies have shown evidence that natural climate variations acting on seasonal and subseasonal time scales may influence the frequency of tornadoes and tornado-favorable environmental conditions. Such climate variations include the El Niño Southern Oscillation (ENSO), Madden-Julian Oscillation (MJO), and Global Wind Oscillation (GWO), among others, and are physically linked via induced modulation of the jet stream, Rossby wave patterns, and associated environmental ingredients favorable for severe thunderstorm and tornado development[2,3,4]. Natural variations acting on decadal timescales (e.g., Atlantic Multidecadal and Pacific Decadal Oscillations) could potentially influence tornado frequency, however they have not been extensively explored due to the relatively short temporal record of tornado observations, rendering uncertainty too high to evaluate their linkage.

Does anthropogenic climate change impact tornado activity?

Despite artificial trends in the SED, there is still a potential role for changes in tornado activity due to human-caused climate change. Given that tornado-producing storms are related to the strength of atmospheric instability, which promotes rising air and thunderstorm formation, and vertical wind shear, which provides the necessary rotation for tornadic thunderstorms (Figure 3), an alternative approach assesses how these proxy indicators of environmental favorability may change due to climate change. In general, human-caused climate change is expected to increase atmospheric instability by increasing temperature and humidity in the lower atmosphere, while simultaneously weakening vertical wind shear through a reduction in the surface pole-to-Equator temperature gradient. Trends in favorable environmental ingredients within the historical climate have begun to emerge[5,6,7], but results can be inconsistent between various datasets[7], and it is unclear whether trends are due to natural variability, anthropogenic climate change, or both[4]. In terms of future climate projections, early research suggested a likely tug-of-war between instability and wind shear, but recent studies have shown an overall increase in projected number of days where sufficient instability and wind shear occur in tandem[2,3,4]. However, analysis of environmental favorability does not account for storm formation, and thus provides an overestimate of severe storm frequency. With increased computing power, high-resolution modeling has become more feasible, and research has explored how the initiation, frequency, organization, and seasonality of severe thunderstorms may change in the future[8,9,10].

Can we predict tornado activity on monthly-to-seasonal time scales?

Because current numerical model forecasts available at extended lead times do not have the resolution necessary for explicitly representing the extremely small-scale tornado structures, the current strategy focuses on the prediction of favorable large-scale patterns and environmental conditions (atmospheric instability and wind shear) in addition to statistical relationships with remote climate signals (e.g., ENSO, MJO, GWO). Emerging research regarding the existence of predictability sources (e.g., climate phenomena) suggest that it may be possible to provide subseasonal prediction of anomalous periods of severe weather activity over the U.S, and experiments to predict severe weather conditions on 2–4 week time-scales have begun[8,9,10,11,12]. However, periods of enhanced forecast skill at these longer lead times, or "forecasts of opportunity", may occur relatively infrequently. On seasonal time scales, the primary source of predictability is derived from ENSO, though a large degree of

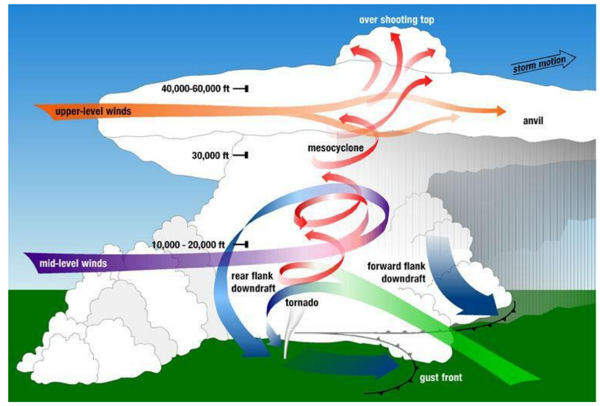

Figure 3: This schematic of a supercell thunderstorm shows how instability and wind shear influences tornado formation. The unstable rising air (red arrows) is forced to rotate by the increased wind speed between the lower (green) and mid-to-upper levels (purple-orange).

variability in seasonal severe weather exists that cannot be explained by ENSO alone. In general, El Niño events tend to result in fewer tornado events over the U.S. during winter and spring with a delayed peak in the annual cycle, while La Niña favors more frequent events and an earlier annual peak[3]. Overall, the viability of providing monthly and seasonal outlooks of tornadoes has not yet reached a level needed to provide actionable information.

The potential for predicting even longer-term tornado activity (i.e., decadal-to-centennial) is much less clear given the inherent uncertainties in the model-based prediction of decadal-to-centennial regional climate change. Large gaps exist in current understanding on all timescales, however, it is widely believed in the scientific community there is great potential for research and modeling to address these scientific questions.

How should research be directed to improve understanding?

Near-term research should target several crucial areas:

- Improve understanding of the influence of large-scale natural climate variations on severe thunderstorm frequency;
- Improve understanding of predictability and predictability sources for extended-range forecasting;
- Improve understanding of potential climate change impacts on the frequency of tornadoes;
- Advance modeling and downscaling strategies;
- Explore ways to develop consistent assessments that exploit recent technological advances in remote sensing of severe storms.

Additional Resources

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