

A brief assessment of the impact of large-scale climate change on severe thunderstorms and tornadoes

This document briefly summarizes our current scientific understanding of: 1) observed changes in severe thunderstorms and tornadoes, and 2) the possible role of human influences in modulating past and future changes in these events. Our goal is to articulate what we know with confidence, what is poorly-understood and contentious, and how scientific understanding might be advanced. Eight members of the newly-formed Climate Science Rapid Response Team (CSRRT)¹ contributed to this response to an informational request from the Office of Science and Technology Policy.² Our response also relies on scientific assessments produced by the Intergovernmental Panel on Climate Change,³ the U.S. Climate Change Science Program,⁴ and the U.S. Global Change Research Program.⁵

Introduction

The recent devastation and loss of life caused by tornadoes (primarily arising from severe tornadoes in Joplin, Missouri; Tuscaloosa, Alabama; and Minneapolis, Minnesota) has sparked vigorous scientific and public debate⁶ about the possible contribution of human activities to changes in tornado behavior. The debate is similar to the scientific and public discourse in the aftermath of the 2005 Atlantic hurricane season, when possible links between human-induced climate change and hurricane intensity were front-page news.

There are some key parallels between the tornado and hurricane debates. Common aspects of both debates include: 1) concerns about the quality of observational data; 2) the current inability of most computer models of the climate system to produce simulations with features recognizable as tornadoes and hurricanes; and 3) the large uncertainties in our scientific understanding of how human activities influence these severe weather events.

Observations of changes in the number and severity of tornadoes are not an immutable gold standard. Since the start of reliable official U.S. tornado records in 1953, there have been important changes in the observing system (such as the introduction of Doppler radar), in the size and distribution of population in U.S. areas affected by tornadoes, and in public awareness of tornadoes.⁴ These non-climatic factors make it difficult to tease out a true climatic signal in the nearly 60-year record of changes in tornado properties. An added complication is that tornadoes are inherently rare phenomena. The relatively short observational record limits our

ability to make reliable statements about the true physical meaning and significance of observed changes in tornado intensity and frequency.

Given these limitations of the observational data, it is important to ask whether numerical models of the climate system can help us to understand the physical processes influencing tornado behavior, how these processes have changed historically, and how they may change in the future. Unfortunately, we currently do not have the computational capability to simulate tornadoes in global or regional climate models – model resolution is not fine enough to represent such small-scale phenomena. This means that we cannot explicitly study tornadoes in today's climate models.

We can, however, use current models to ask reasonable scientific questions about the large-scale environmental conditions which govern tornado behavior. Two of the key conditions are: 1) the convective available potential energy (CAPE), which is a function of the temperature and moisture at low levels of the atmosphere and cool temperatures aloft; and 2) vertical wind shear, which is the difference between winds near the ground and winds at high levels in the atmosphere.

High values of CAPE and wind shear favor the development of severe thunderstorms. Tornadoes develop from severe thunderstorms, and tornado intensity is tightly linked to vertical wind shear.

Historical changes in U.S. tornado behavior/large-scale conditions

Here is what we know with confidence about historical changes in U.S. tornadoes and in large-scale conditions affecting tornadoes:

1. From the 1950s to present, there has been an increase (of roughly 140 tornadoes per decade) in the total number of U.S. tornadoes in the official U.S. database. This increase is almost entirely in the weakest class of tornadoes (F0).
2. There has been a decrease in the number of violent (F4/EF4 and higher) tornadoes over the same period. The number of violent U.S. tornadoes during 2010 and 2011, and in particular the number of EF5 tornadoes in 2011, is unusual in the context of the long-term record.
3. Because of the data and model deficiencies described above, it is difficult to reliably estimate the relative contributions of data quality problems, natural internal climate

variability, and human-caused climate change to the historical trends in total tornadoes and in violent tornadoes.

The recent tornado outbreak of April and May 2011

Here is what we know with confidence about the recent tornado outbreak:

1. U.S. events qualitatively similar to the tornado outbreak of April 27, 2011, have occurred in the past (in 1974, 1932, 1920, 1908, and 1884). The 1974 outbreak was almost certainly a bigger outbreak. We have less reliable information about earlier large outbreaks.
2. April 2011 was the most active April for tornadoes in the official record. When official records are in, it will probably be the most active calendar month ever.
3. April and May 2011 had high values of vertical wind shear. This was the result of anomalously strong middle and upper-atmospheric winds in a band extending west-to-east across the central U.S.
4. April 2011 had unusually high values of low-level moisture in the south-east U.S., apparently due to strong low-level winds passing over the warm tropical Atlantic and Gulf of Mexico. Similar conditions characterized previous spring tornado outbreaks in the south-east U.S.

Computer model simulations of future changes in tornadoes

Here is what computer models tell us about possible future changes in tornado behavior:

1. Simulations from three different climate models suggest that CAPE will increase over the 21st century.⁷ The CAPE increase is primarily driven by atmospheric moistening, which in turn is dependent on surface warming.⁸ Large-scale increases in surface temperature and atmospheric moisture are a robust feature of all model simulations with human-caused changes in greenhouse gases.^{3,4,5}
2. The same simulations point towards a decrease in vertical wind shear over the 21st century. Wind shear is dependent on the equator-to-pole temperature gradient. Since the poles are expected to warm more than the equator, some scientists expect that on average, wind shear should decrease over much of the mid-latitudes.^{7,9} They note that

annual average wind shear conditions can provide useful information about the nature of the tornado season. Other scientists believe that because wind shear is so variable on a day-to-day basis, we need to understand the changes in specific weather situations rather than the changes in average wind shear.

3. The projected CAPE increase and wind shear decrease have countervailing effects on severe storms. For severe thunderstorms, the increase in CAPE is likely to “win out” over a possible decrease in shear. This means that the frequency of large-scale environmental conditions favorable for severe thunderstorms is expected to increase. Our expectations for tornado behavior are more uncertain. The strong dependence of tornadoes on wind shear, coupled with uncertainties in the regional and seasonal details of model projections of 21st century wind shear changes, make it difficult to say with confidence what impact large-scale atmospheric warming will have on tornado occurrence or intensity.
4. Even though model trends of CAPE increase and shear decrease over the 21st century are statistically significant, simulations still show large year-to-year variability in CAPE and shear. This means that even in a warmer, moister climate, we would expect tornado frequency and intensity to vary substantially from one year to the next. This short-term variability in tornado properties is primarily linked to internal “climate noise” associated with the El Niño-Southern Oscillation (ENSO). Phenomena like ENSO (and other modes of “climate noise”) can influence the regional weather patterns and atmospheric conditions conducive to severe thunderstorm and tornado formation. Currently, we do not fully understand how ENSO will change in a warmer world.³
5. The results discussed above are primarily from three climate models. An unpublished analysis of results from a larger number of models (12 to 16) suggests that there may be considerable uncertainty in the geographical pattern (and perhaps even in the sign) of the projected 21st century CAPE and shear changes. Because of this uncertainty, we do not know whether/how large-scale warming and moistening of the atmosphere will alter the geographical distribution of areas affected by severe thunderstorms and tornadoes.

Summary

Human activities have made a substantial contribution to the recent warming of the Earth’s surface and moistening of the atmosphere.^{3,4,5,10} We know this with high confidence.^{11,12,13}

It is very likely that these large-scale changes in climate have influenced – and will continue to influence – many different types of extreme event, such as heavy rainfall,^{3,4,5,14} heat waves,^{3,4,5,15,16} and flooding.^{3,4,5,17} Large-scale climate change is also likely to affect small-scale phenomena like severe thunderstorms and tornadoes. The nature and the degree of influence are very uncertain, particularly for tornadoes.

Model simulations can provide us with useful information about likely changes in the large-scale environmental conditions which affect severe thunderstorms and tornadoes. At present, such simulations cannot actually represent these small-scale phenomena.

Improving our scientific understanding

In view of the destruction and human suffering caused by the tornado outbreak of April and May 2011, it is imperative to improve our scientific understanding of links between large-scale climate change and changes in the properties of tornadoes. Apart from a few pioneering papers,^{7,8} relatively little research has been done in this area.

Progress needs to be achieved on multiple fronts:

1. *Better data.* We need to develop improved observed records of the true changes in tornado frequency and intensity. This will require better ways of removing non-meteorological effects from these records, and better use of other, newer sources of data (like Doppler radar measurements).
2. *High-resolution simulations.* We need to perform and analyze simulations with very high-resolution climate models. This gives us useful information on detailed physical processes affecting the formation and statistical properties of tornadoes.
3. *Exploiting large multi-model archives.* Existing and new archives of climate model simulation output¹⁸ can help us determine how the large-scale environmental conditions which affect tornadoes (like CAPE and wind shear) respond to human-caused changes in greenhouse gases. Are the responses consistent, or do they vary markedly across models? How might CAPE and wind shear change if there were only natural “climate noise”, and no human interference with the climate system? Can models tell us something useful about the relative importance of natural and human influences on CAPE and wind shear? These are all questions we can and should answer.

¹See <http://www.climaterapidresponse.org/about.php>.

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¹⁸An example of an existing archive of climate model simulation output is the Coupled Model Intercomparison Project, phase 3 (CMIP-3). Phase 5 of this project (CMIP-5) is now underway, and will provide simulation results from computer models developed at all of the world's major climate modeling centers.