Advancing the Nation’s capability to anticipate tornado and severe weather risk

Scott Weaver (NOAA/CPC), Jeff Trapp (Purdue University), Michael K. Tippett (IRI), Russell Schneider (NOAA/SPC), Phil Pegion (NOAA/ESRL,CIRES), Sang-Ki Lee (NOAA/AOML), Wayne Higgins (NOAA/CPC), Andy Dean (NOAA/SPC), Greg Carbin (NOAA/SPC), Harold Brooks (NOAA/NSSL), Mike Baldwin (Purdue University), Francisco Alvarez (Saint Louis University)

Abstract

This white paper summarizes existing US tornado and severe weather prediction capability, outlines desired capabilities and presents an implementation plan combining research and institutional strategies for achieving those goals. At present, tornado and severe weather outlooks do not extend beyond one week. Recent tornado outbreaks have been accompanied by increased demand for more information provided with greater antecedence. The latest science gives evidence that tornado activity can be predicted further in advance than was previously believed and provides improved understanding of the links between large-scale climate variability and tornado activity. A focused effort building on current science and available model and data resources would have immediate benefits and represent a substantial step toward desired capabilities. Complementary to the development of new severe weather information is the need to determine how public and private stakeholders can effectively use such information. We recommend a strategy providing resources for research integrated with enhancement of operational capacity.

1. Motivation/Background

Billion dollar weather and climate disasters are on the rise in the US. In 2011 there were a record number (14), six of which were related to tornado outbreaks. Currently, there is no national capacity to provide skillful long-range severe weather outlooks. In response, a workshop was held in May 2012 at the National Weather Center in Norman, Oklahoma to assess the current state of the science and to identify what is required to develop long-range severe weather outlook and attribution products that span the intraseasonal-to-seasonal timescales, incorporate state-of-the-art science and technology, and achieve needs for regional information.

At present the NOAA Storm Prediction Center (SPC) provides severe weather outlooks to 8 days. The recent call for extending the range of extreme weather and climate information, highlighted by the NWS Weather Ready Nation initiative, necessitates that we move toward advancing the science and operational capabilities to expand the severe weather outlooks to the extended (i.e. weeks 2-6) and seasonal (3 months) time horizons. Such information is useful for federal and state government agencies, private industry, emergency planners, and other stakeholders to incorporate into their operational decision making capabilities. Nascent efforts toward this goal are already underway and have demonstrated potential for advancing our long range prediction capabilities. Notwithstanding these recent advances, there are still significant gaps in understanding, and a need for resources to continue advancing the science toward skillful long range severe weather prediction. This white paper outlines a bold vision from the climate and weather science communities with a roadmap on how to accelerate the required scientific advancements necessary to deliver these vital products to the nation.

Our strategy is informed by the emergence and success of hurricane activity forecasts over the past decade or so. Although the physical phenomena are distinct, there are many scientific and institutional parallels including: integrating short-range event forecasts with seasonal activity outlooks; the issue of different products and users for different time-scales; the value of statistical identification of favorable environmental factors; diagnosis of relevant of climate variability factors; the value of high-resolution dynamical modeling; questions about climate change and decadal variability. We are confident that with the current understanding and tools, we will soon be able to achieve long-range severe weather outlooks on par with seasonal hurricane outlooks, thereby enhancing public awareness. In the following sections we describe the desired and current capabilities, the gaps and how they may be filled, recommended activities, and an implementation strategy.

2. Desired Capabilities

To realize the goal of extending the time horizon of useful severe weather outlooks requires the development of capabilities spanning the climate and weather research and operational enterprises. We envision a seamless severe weather information stream that includes event forecasts (1-7 days), extended activity outlooks (greater than one week), and seasonal activity anomalies (1-3 months) with product and confidence intervals varying according to lead time. Advances will also lead to improved support for severe weather attribution capabilities.

To achieve this goal scientific advances are required in the following areas:

1. Ability to diagnose the role of large-scale climate variability, including climate change, on severe weather occurrence supporting attribution of extreme events and improved understanding of the role of low-frequency climate variability in severe weather.

2. A multi-faceted modeling initiative employing global and regional climate modeling to support statistical and dynamical downscaling approaches.

3. An observational record making complete use of available data and technology.

4. Severe weather forecast information feeding into public and private sector decision systems consistent with varying lead-time and levels of certainty.

3. Current capabilities/background

Recent tornado outbreaks over the United States have caused devastating societal impact with significant loss of life and property. Fortunately the Storm Prediction Center (SPC) provided accurate outlook information several days in advance of the major tornado outbreak episodes during the spring of 2011. This increased tornadic event lead time speaks to the recent strides made in the scientific understanding of severe weather outbreaks.

In an effort to build on these successes and advance societal preparedness it is necessary to outline our current capabilities so that we may have a foundation for moving toward extended range severe weather outlooks. Our current capacity includes:

1. Severe weather information up to one week in advance based on understanding of the environment conducive to the development of severe weather outbreaks.

2. Robust relationships between indices of environmental quantities with tornado and other severe weather occurrence.

3. Evidence of the utility of indices constructed from; Reanalyses, GCM-scale forecasts, and high-resolution dynamical downscaling.

4. Indications for the influence of large scale climate variability modes (e.g., ENSO, PDO, AMO, etc.) and other boundary forcing (e.g., soil moisture) on the severe weather environment.

4. Gaps: What are they and how can they be filled

Despite important advances in the foundational knowledge of the severe weather-climate linkage there are significant deficiencies in understanding and prediction that need to be addressed to move toward skillful extended range severe weather outlooks. These gaps include:

- No operational severe weather forecasts beyond week 1.
- Climate variability on monthly and longer timescales is currently not used to constrain severe weather risk.
- Operational climate model resolution is not sufficient to resolve mesoscale variations in the severe weather environment.
- Observational data properties and reliability is complicated and not universally known.
- Precise needs of users including entry points in their decision systems are unknown.

There are many research tools and approaches available to further our understanding of the relationship between climate and the severe weather environment that will assist in the development of operational extended range outlooks. Recent research techniques are beginning to demonstrate the potential for advancement in this critical scientific and societal need.

Large Scale Climate Variability

Given the role of large scale climate variability modes to influence shifts in key midlatitude atmospheric patterns (i.e., upper/low-level jets and trough/ridge placement) it is necessary to advance understanding of the severe weather linkage to slowly evolving climate mechanisms, such as the El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO). Some studies have investigated the ENSO linkages of total U.S. tornado activity to traditional ENSO indices (Marzaban and Schaeffer 2001), and wintertime tornado outbreaks (Cook and Schaeffer 2008), and found weak albeit statistically significant correlations.

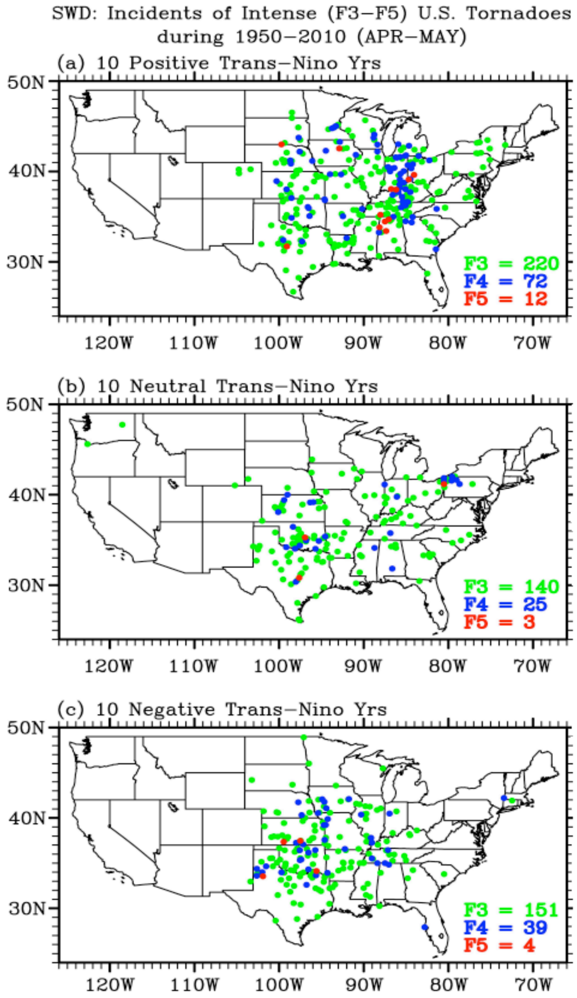

Fig 1. Incidence of F3, F4, and F5 tornadoes during 1950-2010. Panels a, b, and c represent the 10 strongest positive, neutral, and negative Trans Nino years respectively.

However, recent studies indicate that ENSO phase transitions, as captured by the Trans-Nino index (TNI) influence the regional distribution of intense springtime tornadic activity (Figure 1) by modulating the large scale atmospheric circulation (Lee et al. 2012), one byproduct of which is an eastward shift of the North American Low-level jet (NALLJ) that supports stronger moisture convergence and low-level wind shear over the southeast U.S. and coincident increases in tornadic activity there (Weaver et al. 2012). Furthermore, there is emerging evidence for the role of the PDO and AMO in fostering environmental conditions supportive of tornado activity.

Despite this recent progress our understanding of these connections has not yet achieved a level of maturity commensurate with that necessary to provide probabilistic outlooks. One of the critical areas that require our immediate attention is ENSO phase transition in springtime and the associated atmospheric teleconnections to the U.S. Additionally, for this effort to span the intraseasonal to seasonal time horizon, it is important that severe weather linkages to shorter duration climate variability modes be explored. These may include; the Madden Julian Oscillation (MJO), Arctic Oscillation (AO), and Pacific North American pattern (PNA), to name a few. While extended range predictability of the AO and PNA continues to be a challenge, recent advancements in MJO prediction out to weeks 3-4 has recently been demonstrated in some climate modeling systems (Wang et al. 2013; and references therein).

Model Resolution

The current generation of global climate models cannot explicitly represent tornadoes and thunderstorms, because these phenomena are effectively subgrid-scale processes.

As such, downscaling techniques are typically employed to extract severe weather information. These techniques typically involve either directly using the coarse resolution but computationally inexpensive global climate model output to relate large-scale climate parameters to the occurrence of tornadoes and thunderstorms, or using the global model to drive a much higher-resolution regional climate or weather model. Both approaches have benefits and drawbacks.

Coarse grid global climate models will have issues with adequately representing the characteristic mesoscale circulations and boundaries that are important for triggering severe weather. As such their usefulness is limited to direct statistical downscaling of large scale environmental parameters to tornado and severe weather occurrence. Nevertheless, operational global climate model predictions are generated by modeling centers on a frequent (daily for NCEP) allowing direct statistical downscaling methodologies to be mined immediately for operational capabilities. Using observed relationships between large scale environmental parameters and tornado occurrence Tippet et al. (2012) demonstrate skill in predicting monthly tornado counts from the output of the NCEP Climate Forecast System. Figure 2 shows a scatter plot of the predicted June tornado occurrence vs. the observed for each year from 1982-2010. In many years the CFS output was able to approximate the number of observed tornadoes. While the potential predictability of this technique has not been quantified, CFS model development activities aimed at improving the skill of large scale climate variability will lead to coincident skill in predicting monthly-seasonal tornado occurrence.

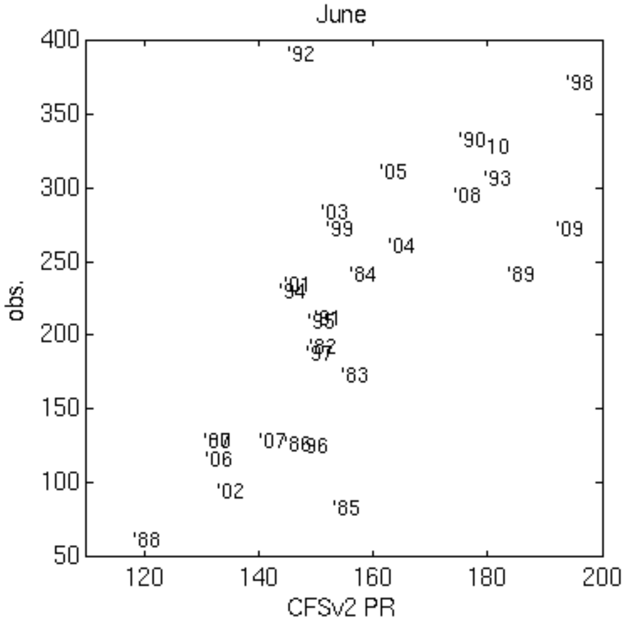

Fig 2. Scatter plot of observed with 0 month lead CFSv2 forecast model based predicted number of June tornadoes 1982-2010. The 2 digit number indicates the year.

Although this and other statistical downscaling approaches show promise, a key issue is the lack of an explicit treatment of the “triggering” or initiation of convective storms. Indeed, although the current generation of high-resolution global and regional models might be capable of representing some mesoscale circulations, they still cannot resolve individual convective storms. Consequently, it is not known for certain whether storms would actually occur and realize the environmental conditions predicted by these models.

Trapp et al. (2010) demonstrate the viability of using global-scale reanalysis data as initial and boundary conditions for high-resolution(~4-km gridpoint spacings) weather forecast models; their ongoing work similarly demonstrates the viability of using global climate models, including the CFS, in such a dynamical downscaling approach. The forecast model – Weather Research and Forecasting (WRF) model – is configured such that convective clouds and storms are explicitly represented over the entire domain. The output of such convection-permitting WRF-model integrations over months and seasons is then mined to determine the spatial distribution and frequency of convective storms by type and severity. Figure 3 shows an example of a predicted severe storm occurrence over the period April through June of 2012, generated by WRF-enabled downscaling of the CFS model.

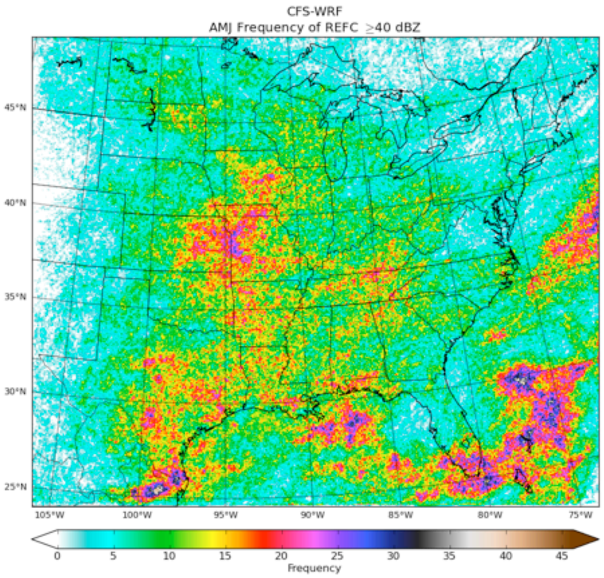

Fig 3. Example of predicted storm occurrence (simulated radar reflectivity > 40 dBZ) over the period April, May, Jun, 2012, generated by WRF enabled downscaling of the CFS model.

Observational Databases

Underpinning our current understanding of the severe weather environment and its climate connections is a long term (1950-present) historical database of F-scale tornado counts. Since this database was not intended to be a consistent homogenous long-term climate record of tornadic and severe weather parameters, there are inherent inconsistencies as a result of public awareness, tornado reporting practices, NWS guidelines, and other sources of inhomogeneity. These issues may introduce spurious trends in the long-term tornado data. However, it has been demonstrated that much of this trend can be ameliorated by focusing on the F1-F5 tornado counts only (Verbout et al. 2006) as demonstrated in Figure 4 which shows that much of the trend can be explained through the timeseries evolution of the F0 tornado counts. Nevertheless, it is necessary to explore other novel ways to further homogenize the long–term historical tornado database while simultaneously taking

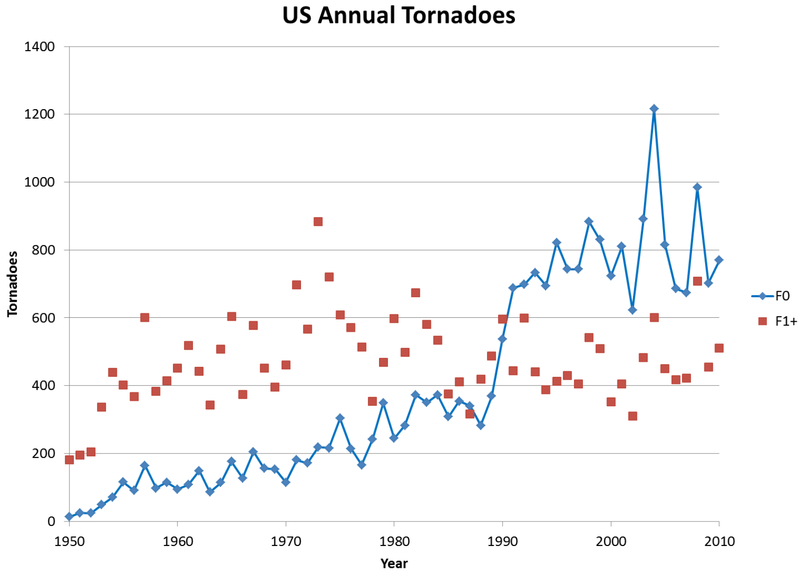

Fig 4. Time series of F0 (blue) and F1 nd greater (red) annual tornado counts for 1950-2010.

advantage of modern technological advances (i.e., Doppler radar) to develop new techniques to constrain the recent (last 15 years) tornado record and continue into the future. Tornado database issues are discussed more thoroughly in Brooks et al. (2003) and Doswell et al. (2009).

Societal Needs

Extended range severe weather information will result in a better informed and prepared society, however, it is still unclear what the precise needs of users may be and where the entry points are to their decision systems. As such a critical piece of this endeavor is to engage stakeholders as to how their decision making would be affected by providing probabilistic severe weather information from intraseasonal to seasonal timescales.

5. Recommended Implementation Strategies

We recommend a strategy that integrates basic and applied research with enhancement of operational capacity. This will be achieved through programmatic climate research funding calls and development of committed partnerships between the operational and research communities. We suggest the following two-pronged approach:

A. Topics for targeted research funding calls

Role of Large Scale Climate Variability

- Increase our fundamental understating of ENSO phase transitions and the associated teleconnections to the U.S. in springtime.
- Assess and improve our current seasonal predictability of ENSO phase transitions and the associated teleconnections to U.S. in springtime.
- Continue to explore long term climate signals (e.g., TNI, ENSO, PDO, AMO) that may provide predictability on seasonal and longer timescales.
- Investigate severe weather connectivity to intraseasonal climate variability modes (e.g., MJO, PNA, AO, etc.).

Modeling

- Continue to develop and refine severe weather proxy indices and their potential predictability in operational climate models.
- Develop and test dynamical downscaling techniques for explicit severe weather description.
- Explore efforts to study the influence of large scale environments on the initiation of tornadoes and other severe weather phenomena using ultra fine-scale models.

Observational Data

- Establish best practices for use of the existing Severe Weather Database (SWD). For example, using tornado days and tracks may be better suited for diagnostic studies.
- Homogenize the existing SWD by exploring how increases in population size and improvements in tornado detection technology etc. are related to observed numbers of tornadoes.
- Mine the Grazulis data base (Grazulis 1993) for longer term studies. This tornado dataset may not suffer from as many human-induced inconsistencies given that it was developed by a single individual with a consistent methodology.
- Develop a high-quality consistent data set based on ~16 years of Doppler radar. While this may not be long enough timeseries for interannual to decadal climate diagnostic studies, it is apt to be very useful for the continued development of proxy tornadic indicators and intraseasonal climate variability studies.

Users

- Identify stakeholders who are impacted by severe weather and could benefit from incorporating this information into their planning and decision making systems.
- Communicate with stakeholders to feedback their needs to the research community.

B. Operational Coordination

NOAA Operations

- Enhance institutional collaboration between NOAA stakeholders (e.g., CPC, SPC, NSSL, GFDL, etc.), other federal agencies, and academic partners.
- Coordination of time-scales of forecasts and projections (e.g., SPC - CPC).
- Human resource allocations

Research to operations

- Establish an experimental testbed for spring seasonal severe weather prediction to begin as early as 2014. The testbed will combine scientific and operational expertise from academic and federal partners to assess the viability of standing up a seasonal severe weather forecast system.
- Increased computing infrastructure for transitioning research into NOAA operations
- Support for specific collaboration between researchers and practitioners and more generally between the severe weather and climate communities including scientific visiting appointments, shared post-docs, and funding that requires collaboration.

Operations to research

- Institutional support for attribution activities to feedback into the forecast process
- Leveraging Existing NOAA Resources (i.e., CFS data, GFS reforecast, GFDL time-slice experiments, and the National multi-model ensemble efforts).

6. References

Brooks, H. E., C. A. Doswell, III, and M. P. Kay, 2003: Climatological estimates of local daily tornado probability for the United States. *Wea. Forecasting*, **18**, 626-640.

Grazulis, T.P., 1993: *Significant tornadoes* 1680-1991. Environmental Films, St. Johnsbury, VT, 1326 pp.

Lee, S.-K., R. Atlas, D. Enfield, C. Wang, and H. Liu, 2012: Is there an optimal ENSO pattern that enhances large-scale atmospheric processes conducive to tornado outbreaks in the U.S? J. Clim., in press.

Marzaban, C., and J. T. Schaefer, 2001: The correlation between U.S. tornadoes and Pacific sea surface temperatures. *Mon. Wea. Rev.,* **129,** 884-895.

Tippett, M. K., A. H. Sobel, and S. J. Camargo, 2012: Association of U.S. tornado occurrence with monthly environmental parameters. *Geophys. Res. Lett*, **39**, 6 pp., doi:10.1029/2011GL050368.

Trapp, R. J., E. D. Robinson, M. E. Baldwin, N. S. Diffenbaugh, and B. R. J. Schwedler, 2010: Regional climate of hazardous convective weather through high-resolution dynamical downscaling. *Climate Dynamics*, doi: 10.1007/s00382-010-0826-y.

Verbout, S. M., H. E. Brooks, L. M. Leslie, and D. M. Schultz, 2006: Evolution of the U.S. tornado database: 1954-2003. *Wea. Forecasting,* **21,** 86-93.

Weaver, S. J., S. Baxter, and A. Kumar, 2012: Climatic role of North American low-level jets on U.S. regional tornado activity. *J. Clim*. **25,** 6666-6683.

Wang, W., et al., 2013: MJO prediction in the NCEP CFS version 2. Climate Dynamics, accepted pending minor revisions.