Project Title: **Toward developing a seasonal outlook for the occurrence of major U.S. tornado outbreaks**

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1. Project goals and summary and accomplishments

Recent tornado outbreaks over the U.S. have caused devastating societal impacts with significant loss of life and property, prompting the need to identify and understand long-term climate signals that may provide seasonal predictability for intense tornado outbreaks over the U.S. Currently, seasonal forecast skill for intense U.S. tornado outbreaks has not been demonstrated. Therefore, the main goals of this project are (1) to refine the recently identified potential predictive skill provided by the Trans-Niño (TNI), (2) to explore other long-term climate signals that can provide additional predictability in seasonal and longer time scales, and (3) to evaluate and potentially improve seasonal forecast skill for intense U.S. tornado outbreaks in the NCEP Climate Forecast System version 2 (CFSv2).

In order to achive these goals, we found an urgent need to better characterize springtime El Niño-Southern Oscillation (ENSO) evolution beyond the Trans-Niño (TNI) index, which was the only index used to characterize springtime ENSO phases in Lee et al. [2013]. We first attempted to characterize springtime ENSO evolution into onset, decay, resurgent and transition phases, and found that there are unique and significant patterns of springtime US rainfall anomalies frequently appearing during those springtime ENSO phases [Lee et al., 2014a]. Based on this finding, we further used a more systematic method to objectively identify the four dominant springtime ENSO phases (i.e., persistent versus early-terminating El Niño and resurgent versus transitioning La Niña), which explain about 35% of ENSO variance [Lee et al., 2014b]. In the subsequent study [Lee et al., 2016], we showed that these four springtime ENSO phases are linked to distinct and significant US regional patterns of outbreak probability, and also identified that the North Atlantic SST tripole varibiality could provide additional seaonal predicatbility of US regional tornado outbreaks.

Based on our scientific advancements in the subjects of springtime ENSO diversity and its impact on US tornado outbreaks, which led to three publications [Lee et al., 2014a; 2014b and 2016]. we built a hybrid statistical-dynamic seasonal tornado prediction model. We applied this model for the 2016 spring season (March-May) and provided the forecast to NOAA/CPC. Our forecast for the 2016 tornado season was used as one of the several models for the NOAA/CPC 2016 Seasonal Severe Weather Outlook (Experimental).

The PIs of this project also organized *climate and severe weather workshop* (March 11-12, 2015) at NOAA/CPC, and wrote a white paper "*Advancing the Nation's capability to anticipate* *tornado and severe weather risk*", which was widely distributed within academic and seasonal forecast community and beyond.

Here, we briefly describe the following achievements.

1) Springtime ENSO phase evolution and its relation to rainfall in the U.S.
2) White paper: *Advancing the Nation's capability to anticipate tornado and severe weather risk*
3) Spring persistence, transition, and resurgence of El Niño
4) Climate and severe weather workshop (March 11-12, 2015)
5) US regional tornado outbreaks and their links to spring ENSO phases and North Atlantic SST variability
6) NOAA 2016 Seasonal Severe Weather Outlook (Experimental) for March-May 2016
7) A hybrid statistical-dynamic seasonal tornado prediction model

2.1 Springtime ENSO phase evolution and its relation to rainfall in the U.S.

Although this task is not explicitly listed in the proposed tasks, the PIs have found no comprehensive study or documentation of the springtime ENSO phase evolution, which provides the fundamental basis for the climate - tornado linkage. Therefore, we have decided that it is a necessary and important step to explore and document various types of ENSO phase evolution in spring and their relationship to rainfall variability in the U.S.

<u>Summary</u>

Shortly after reaching its peak in boreal winter, ENSO decays very rapidly in spring (i.e., May, April and May). Therefore, the ENSO SST anomalies during this time are usually much weaker in amplitude and their spatial structures become much less coherent compared to those during the peak season, and thus the correlation between ENSO and the U.S. climate start to break down after late winter or early spring [e.g., Mo 2010].

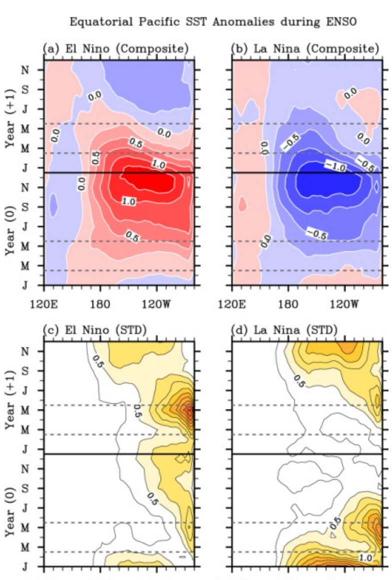

Figure 1. Composites of tropical Pacific SST anomalies during (a) El Niño and (c) La Niña averaged between 2^{o}S and 2^{o}N. The standard deviations are also shown in (b) and (d) for El Niño and La Niña, respectively. To produce these composites, we selected 21 El Niño events and 21 La Niña events during the period of 1949 – 2012 based on the Climate Prediction Center's criteria (i.e., SST anomalies averaged in Nino3.4 (120W^{o} – 170W^{o} and 5S^{o} – 5N^{o}) must exceed 0.5^{o}C for a minimum of 5 consecutive over-lapping seasons) using the Extended Reconstructed Sea Surface Temperature version 3b (ERSST3), a blended satellite and in situ analysis of global monthly SST on a 2^{o} longitude by 2^{o} latitude grid [Smith et al., 2008].

Indeed, as shown in **Figure 1a and b**, the ENSO composite SST anomalies in the eastern Pacific (EP hereafter) terminate rather abruptly and almost completely dissipate by March (+1) or April (+1) - any month in ENSO onset year is identified by suffix (0) whereas any month in ENSO decay year is denoted by suffix (+1) hereafter. Interestingly, the SST anomalies in the central Pacific (CP hereafter), on the other hand, weaken much more gradually and persist throughout the spring until around June (+1). As a result, a rather robust zonal gradient of SST anomalies forms along the equatorial Pacific between CP and EP during the decay phase of ENSO.

Every ENSO event is unique and somewhat different from one another [Trenberth and Stepaniak, 2001]. As shown in **Figure 1c and d**, this is especially true during the springtime ENSO phase evolution especially in EP. During the decay phase, the SST anomalies in EP often switch to the opposite sign producing a zonal seesaw pattern between CP and EP. In some cases, they further lead to the onset of another ENSO event with the opposite sign in the subsequent months (e.g., 1987-1988 El Niño; 1964-1965 La Niña). In other cases, the zonal seesaw pattern dissipates altogether during or after spring (e.g., 1994-1995 El Niño; 2007-2008 La Niña). In rare cases, the SST anomalies in EP persist much longer than those in CP, as reported for the decay of the two extreme El Niños in 1982-1983 and 1997-1998 [Lengaigne and Vecchi, 2009].

During the onset phase, on the other hand, the zonal gradient of SST anomalies between CP and EP is generally weaker (**Figure 1a and b**). During the onset phase of La Niña, cold SST anomalies develop in both EP and CP [e.g., McPhaden and Zhang, 2009]. The onset phase of El Niño is more complicated. During this phase, warm SST anomalies usually emerge in both EP and CP. As reported and studied by many, before the late 1970s the warm SST anomalies developed earlier in EP and propagated to CP, whereas after the late 1970s the time-lag relationship between CP and EP reversed [e.g., Wang, 1995; Fedorov and Philander, 2000; 2001; Wang and An, 2001; 2002; McPhaden and Zhang, 2009].

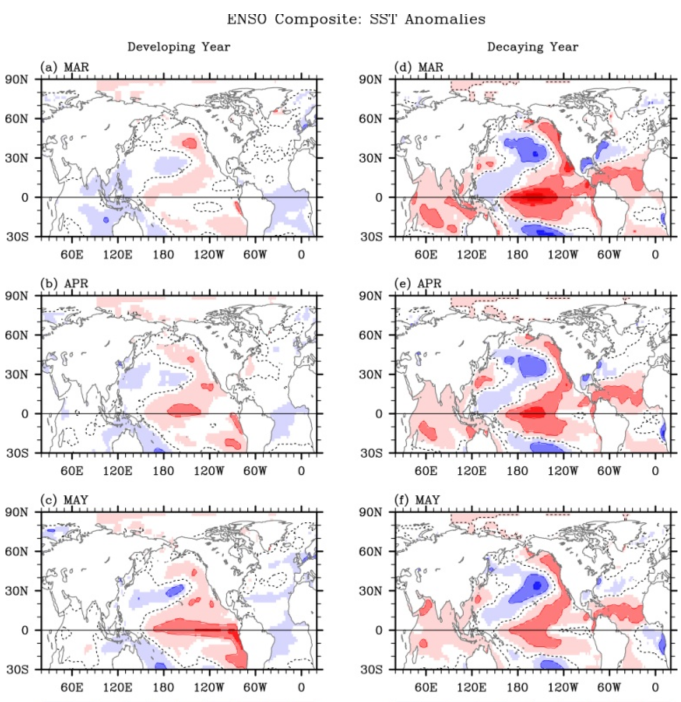

Figure 2. Composite maps of SST anomalies for the developing (left panels) and decaying (right panels) phases of ENSO for the months of March, April and May. The composite maps are computed by first averaging the SST anomalies for the 21 El Niño events then subtracting those for the 21 La Niña events. A statistical test (student-t test) is performed for each grid point by examining a null hypothesis that the composite mean of SST anomalies for El Niño is statistically not different from that for La Niña at 90% confidence level. Only the statistically significant portions are shaded.

It is important to recall that the ENSO SST anomalies evolve rapidly during the onset and decay phases. Therefore, in order to explore and describe them properly, it is important to examine their temporal evolutions and the spatial patterns all-together. **Figure 2** shows the composite maps of SST anomalies for the developing (left panels) and decaying (right panels) phases of ENSO for the months of March, April and May. To produce these composite maps, we selected 21 El Niño events and 21 La Niña events during the period of 1949 – 2012 based on the Climate Prediction Center's criteria (i.e., SST anomalies averaged in Nino3.4 (120W^{o} – 170W^{o} and 5S^{o} – 5N^{o}) must exceed 0.5^{o}C for a minimum of 5 consecutive over-lapping seasons) using the Extended Reconstructed Sea Surface Temperature version 3b (ERSST3), a blended satellite and in situ analysis of global monthly SST on a 2^{o} longitude by 2^{o} latitude grid [Smith et al., 2008]. Shown in **Figure 2** are the composite maps of SST anomalies for the 21 El Niño events subtracted from those for the 21 La Niña events. A statistical test (student-t test) is performed for each grid point by examining a null hypothesis that the composite mean of SST anomalies for El Niño is statistically not different from that for La Niña at 90% confidence level. Only the statistically significant portions are shaded.

It is clear that during an onset year the ENSO SST anomalies are quite negligible in March. But, they grow rapidly afterwards. By May, they achieve a robust spatial pattern, which appears to be a canonical ENSO pattern with the same sign of SST anomalies in CP and EP. During a decay year, on the contrary, the ENSO SST anomalies are quite robust in March, especially in CP. But, they decay rapidly afterwards. By May, the SST anomalies drop below 0.5^{o}C everywhere in the tropical Pacific. It is also important to point out that during a decay year the SST anomalies in EP are statistically not significant, suggesting that either warm or cold SST anomalies may occur for any given ENSO event regardless of the sign of SST anomalies in CP.

To sum up, the tropical Pacific SST anomalies during the onset and decay phases of ENSO in spring are generally much weaker in amplitude, and their spatial structures are more complex and somewhat inconsistent between ENSO events. Nevertheless, it appears that their zonal patterns can be readily categorized into two types. *The first type has a rather strong zonal gradient of SST anomalies between CP and EP and occurs predominantly during the early spring (i.e., March) in a decay year. The second type has a weaker zonal gradient of SST anomalies between CP and EP, with the same sign in EP and CP, and more commonly occurs during the late spring (i.e., May) in an onset year*.

We have also performed further analyses on two special cases of ENSO phase evolution in spring, namely the transition phase and the resurgence phase (not shown). These special cases describe the ENSO phase evolutions in spring during which an ENSO dissipates while another ENSO emerges at the same time. The ENSO event that follows the first event has the opposite sign for the transition phase, and the same sign for the resurgence phase. We find that during the transition phase, the SST anomalies in CP dissipate quickly and the SST anomalies of the opposite sign emerge in EP shortly after March. In May, the SST anomalies in EP exceed 0.5^{o}C and propagate westward. The resurgence phase is characterized by persistent SST anomalies in CP throughout the spring months. Only in May, the SST anomalies in EP are as robust as those in CP.

Lee, S.-K., B. E. Mapes, C. Wang, D. B. Enfield and S. J. Weaver, 2014: Springtime ENSO phase evolution and its relation to rainfall in the continental U.S. *Geophys. Res. Lett.*, 41, 1673-1680. doi:10.1002/2013GL059137. http://www.aoml.noaa.gov/phod/docs/2013GL059137.pdf

2.2 White paper: Advancing the Nation's capability to anticipate tornado and severe weather risk

<u>Summary</u>

S. Weaver, has lead authored a white paper entitled "*Advancing the Nation's capability to anticipate tornado and severe weather risk*". Scientists who have contributed to the whitepaper, include NOAA scientists (S. Weaver, R. Schneider, S.-K. Lee, W. Higgins, A. Dean, G. Carbin, H. Brooks) as well as scientists from academia (J. Trapp, M. Tippett, M. Baldwin, and F. Alvarez). The white paper builds on two workshops that the PIs have attended over the past year and is aimed at developing the scientific capacity to deliver long-range severe weather outbreaks.

The white paper summarizes existing U.S. 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.

2.3 Spring persistence, transition, and resurgence of El Niño

<u>Summary</u>

In Lee et al. [2013], we identified a link between U.S. tornado outbreaks and one particular pattern of springtime ENSO phase, namely a positive phase of Trans-Niño. In Lee et al. [2014a], we explored the onset, decay, transition and resurgence phases of ENSO in spring and their impacts on springtime US rainfall variability. In this study, we further attempted to objectively identify and explain the spatio-temporal evolution of inter-event El Niño and La Niña variability in the tropical Pacific for the entire lifespan from onset to decay.

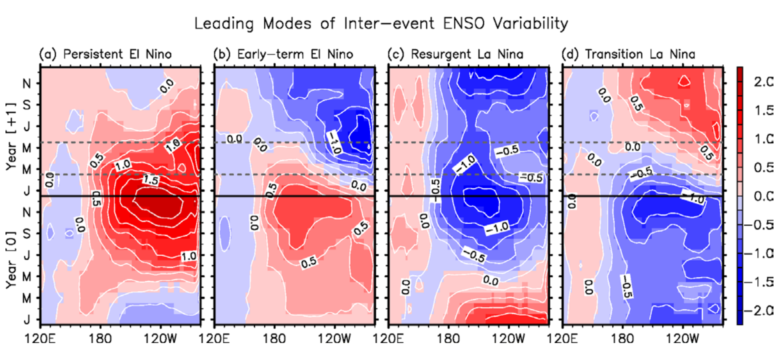

Figure 3. Four leading patterns (Time-longitude plots) of spatio-temporal ENSO evolution identified in Lee et al. (2014b), namely (a) persistent El Niño, (b) early-terminating El Niño, (c) resurgent La Niña, and (d) tranistioning La Niña.

The inter-El Niño variability is captured by two leading orthogonal modes, which explain more than 60% of the interevent variance. The first mode illustrates the extent to which warm SST anomalies (SSTAs) in the eastern tropical Pacific (EP) persist into the boreal spring after the peak of El Niño. Our analysis suggests that a strong El Niño event tends to persist into the boreal spring in the EP, whereas a weak El Niño favors a rapid development of cold SSTAs in the EP shortly after its peak (Figures 3a and 3b). The second mode captures the transition and resurgence of El Niño in the following year. An early-onset El Niño tends to favor a transition to La Niña, whereas a late-onset El Niño tends to persist long enough to produce another El Niño event. The spatiotemporal evolution of several El Niño events during 1949–2013 can be efficiently summarized in terms of these two modes, which are not mutually exclusive, but exhibit distinctive coupled atmosphere-ocean dynamics.

We also applied the same methodology to explore inter-event La Nina variability to find that the first EOF mode of inter-La Niña variability describes El Niño transitioning to a 2-year La Niña and a 2-year La Niña transitioning to El Niño (Figure 3c and 3d).

Lee, S.-K., P. N. DiNezio, E.-S. Chung, S.-W. Yeh, A. T. Wittenberg and C. Wang, 2014: Spring persistence, transition and resurgence of El Nino. Geophys. Res. Lett., 41, 8578-8585, doi:10.1002/2014GL062484. http://www.aoml.noaa.gov/phod/docs/2014GL062484.pdf

2.4 Climate and severe weather workshop

Summary

Scott Weaver (co-PI from CPC) and Gregory Carbin (SPC) co-organized the Climate and Severe Weather workshop (CSWW) at the NOAA Center for Weather and Climate Prediction (NCWCP) in College Park, MD on March 11-12, 2015. The workshop was designed to advance the goal of establishing long-range (i.e., > 1 week) operational severe weather outlooks by enhancing research and development activities, and strengthening partnerships for transitioning research to operations through a multi-institutional collaborative outlook process. The CSWW is the third in a series of workshops on long-range severe weather outlooks. It is the first to include specific discussion and recommendations of how scientific advances in climate and severe weather research may be brought to bear on long-range NOAA operations and applications.

Participants included those from various NOAA/NCEP and NOAA/OAR centers (SPC, CPC, and AOML), NOAA's Climate Program Office, and the academic research community. A key outcome is the recommendation that three severe weather outlooks be developed as a function of varying lead-times. These include separate outlooks for the seasonal, monthly, and weeks 1-4 time horizon. While the continued development of these outlooks will require additional resource commitments from NOAA and other funding agencies, it was widely agreed that experimental implementation could begin in FY 2016.

The CSWW organizing committee proposed 4 goals for consideration at the workshop. Research on the climate and severe weather connection has been rapidly advancing over the last few years. As such, these goals reflect the desire to assess the latest state-of-the-art science and develop a strategy for initiating and strengthening the R2O and O2R paradigms in the long-range severe weather context. The workshop featured four sessions, which included scientific presentations spanning numerous topics and timescales. Session 1 provided an overview of NOAA climate programs and examples of current operational climate outlook

frameworks. Sessions 2 and 3 were oriented toward current understanding of sub-seasonal and seasonal variability of severe weather, respectively, including linkages to climate variability modes (i.e., MJO, GWO, ENSO) and modeling tools for their prediction. Session 4 targeted regional variability and high resolution modeling approaches. The CSWW agenda, list of attendees, and scientific presentations may be found here:
http://www.spc.noaa.gov/misc/CSWW-2015/

Outcomes and Recommendations
The participants discussed implementation planning for operational severe weather outlooks beyond week-1. In particular, it is recommended that three severe weather outlooks be developed as a function of lead-time. These include separate outlooks for the seasonal, monthly, and weeks 1-4 time horizons. While some overlap in severe weather definitions and presentation format may occur, it was decided that some aspects will be unique to the particular lead time of the outlook

Partnerships for scientific research and product dissemination
A critical aspect to the success of this endeavor is to nurture shared activities among the NOAA/NCEP centers (i.e., CPC and SPC), NOAA/OAR labs (i.e., NSSL and AOML) and the academic research community. Despite the optimistic appraisal among the CSWW participants regarding the potential for skillful long-lead severe weather outlooks, it is paramount to understand that forecast improvements and related scientific advances ultimately depend on increased resource support from climate programs engaged in advancing scientific research and development activities. Given that gaps remain in understanding the climate and severe weather linkage and developing applied forecasting techniques, it is necessary that both basic and applied research continue in earnest, focusing on statistical and dynamical modeling, improved diagnostic understanding, and applied research on methods to blend models into useful guidance products.

2.5 US regional tornado outbreaks and their links to spring ENSO phases and North Atlantic SST variability

Summary
Recent violent and widespread tornado outbreaks in the US, such as occurred in the spring of 2011, have caused devastating societal impact with significant loss of life and property. At present, our capacity to predict US tornado and other severe weather risk does not extend beyond seven days. In an effort to advance our capability for developing a skillful long-range outlook for US tornado outbreaks, here we investigate the spring probability patterns of US regional tornado outbreaks during 1950–2014. We show that the four dominant springtime El Niño-Southern Oscillation (ENSO) phases (persistent versus early-terminating El Niño and resurgent versus transitioning La Niña) and the North Atlantic sea surface temperature tripole variability are linked to distinct and significant US regional patterns of outbreak probability (Figure 4). These changes in the probability of outbreaks are shown to be largely consistent with remotely forced regional changes in the large-scale atmospheric processes conducive to tornado outbreaks. An implication of these findings is that the springtime ENSO phases and the North Atlantic SST tripole variability may provide seasonal predictability of US regional tornado outbreaks.

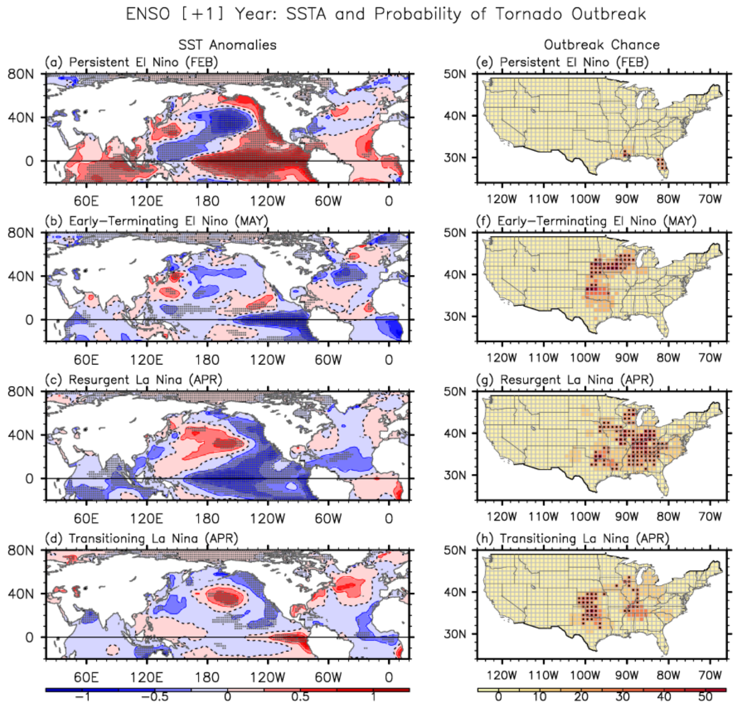

Figure 4. SSTAs and probability of US regional tornado outbreaks linked to the four dominant springtime ENSO phases. Composite (a)–(d) SSTAs for the four dominant phases of springtime ENSO evolution and (e)–(h) the corresponding probability of US regional tornado outbreaks for the month in which each of the four springtime ENSO phases has the strongest influence. The gray dots in panels (a)–(d) indicate that the SSTAs are statistically significant at the 10% level based on a student-t test. The black dots in panels (e)–(h) indicate that the probability of tornado outbreaks is statistically significant at the 10% level based on a binomial test. The units are in °C for the SSTAs and in % for the probability of tornado outbreaks.

This work was presented in the 2015 AGU Fall Meeting (December 14 – 18, 2015) and published in April, 2016 issue of Environmental Research Letters (ERL). In this paper, we showed that the four dominant springtime ENSO phases (persistent versus early-terminating El Niño and resurgent versus transitioning La Niña) and the North Atlantic sea surface temperature tripole variability are linked to distinct and significant US regional patterns of outbreak probability. Therefore, this paper directly contributes to the first two goals of our MAPP project: (1) to refine the recently identified potential predictive skill provided by the TNI, (2) to explore other long-term climate signals that can provide additional predictability in seasonal and longer time scales.

Lee, S.-K., A. T. Wittenberg, D. B. Enfield, S. J. Weaver, C. Wang and R. Atlas, 2016: Springtime U.S. regional tornado outbreaks and their links to ENSO flavors and North Atlantic SST variability. Environ. Res. Lett., 11, 044008, doi:10.1088/1748-9326/11/4/044008. http://iopscience.iop.org/article/10.1088/1748-9326/11/4/044008

Video abstract of this paper can be found at
https://www.youtube.com/watch?v=nOZhWaKy0uw

This paper was also highlighted by multiple NOAA websites: NOAA.gov, Climate.gov, CPO.noaa.gov and research.noaa.gov:

NOAA.gov:
http://www.noaa.gov/ocean-temperatures-may-hold-key-predicting-tornado-outbreaks
Climate.gov:
http://www.climate.gov/news-features/featured-images/could-enso-flavors-help-scientists-predict-regional-tornado-outbreaks
CPO.NOAA.gov:
http://cpo.noaa.gov/AboutCPO/AllNews/TabId/315/ArtMID/668/ArticleID/495470/Spring-

ENSO-Variations-and-North-Atlantic-SSTs-Could-Help-Long-Range-Prediction-of-US-Tornado-Outbreaks.aspx
Research.NOAA.gov:
http://research.noaa.gov/News/NewsArchive/LatestNews/TabId/684/ArtMID/1768/ArticleID/11687/Ocean-temperatures-may-hold-key-to-predicting-tornado-outbreaks.aspx

2.6 NOAA 2016 Seasonal Severe Weather Outlook (Experimental) for March-May 2016

Summary

Arun Kumar (co-PI from CPC) and Gerry Bell (CPC) organized NOAA Seasonal Severe Weather (SSW) outlook tele-conferences in February 2016. Severe storm and climate forecast experts from CPC, AOML, the Storm Prediction Center (SPC), and the International Research Institute for Climate and Society (IRI) participated the conferences and presented multiple prediction models and decision tools. The team's goal is to eventually issue seasonal outlooks for tornado activity before the tornado season begins, which is in March. A lot of progress has already been made this year toward developing seasonal tornado outlooks, both in terms of the science behind the outlooks, and in developing the necessary prediction tools and models to make an outlook. A lot of work has also focused on how such an outlook might be conveyed to the public. However, making a seasonal tornado outlook is very challenging, and there is still a lot of work to be done before such an outlook is issued operationally.

Based on the predication models and decision tools presented during the SSW tele-conferences, NOAA CPC SSW outlook (experimental) for 2016 was completed on February 26, 2016. However, the 2016 outlook was not released to the public. The SSW tele-conference will resume in Februaty 2017.

2.7 A hybrid statistical-dynamic seasonal tornado prediction model

Summary:

We built a hybrid statistical-dynamical seasonal tornado prediction model that uses CFSv2 ensemble forecasts of March-May SST anomalies. Three predictors are derived from the 1st and 2nd EOF modes of tropical pacific SST anomalies and the 1st EOF modes of North Atlantic SST anomalies [Lee et al. 2016)] Partial linear regression in the context of multiple linear regression analysis is used with the three predictors to forecast tornado counts and tornado days for March-May. This model was presented and used as one of the main prediction models for the 2016 NOAA CPC SSW outlook (experimental). An application of the hybrid statistical-dynamical model for the 2016 tornado season is attached to this progress report.

This work directly contributes to the third goal of our MAPP project: (3) to evaluate and potentially improve seasonal forecast skill for intense U.S. tornado outbreaks in the NCEP Climate Forecast System version 2 (CFSv2).

3. Publications and Presentations

Lee, S.-K., B. E. Mapes, C. Wang, D. B. Enfield and S. J. Weaver, 2014a: Springtime ENSO phase evolution and its relation to rainfall in the continental U.S. *Geophys. Res. Lett.*, 41, 1673-1680. doi:10.1002/2013GL059137.
http://www.aoml.noaa.gov/phod/docs/2013GL059137.pdf

Lee, S.-K., P. N. DiNezio, E.-S. Chung, S.-W. Yeh, A. T. Wittenberg and C. Wang, 2014b: Spring persistence, transition and resurgence of El Nino. Geophys. Res. Lett., 41, 8578-8585, doi:10.1002/2014GL062484. http://www.aoml.noaa.gov/phod/docs/2014GL062484.pdf

Lee, S.-K., A. T. Wittenberg, D. B. Enfield, S. J. Weaver, C. Wang and R. Atlas, 2016: Springtime U.S. regional tornado outbreaks and their links to ENSO flavors and North Atlantic SST variability. Environ. Res. Lett., 11, 044008, doi:10.1088/1748-9326/11/4/044008. http://iopscience.iop.org/article/10.1088/1748-9326/11/4/044008

Lee, S.-K., R. Atlas, D. B. Enfield, C. Wang, and H. Liu, Springtime ENSO phase evolution and U.S. tornado activity, AMS annual meeting, February 2 - 6, 2014, Atlanta, GA.

Lee, S.-K., A. T. Wittenberg, D. B. Enfield, S. J. Weaver, C. Wang and R. Atlas, Springtime ENSO flavors and their impacts on US regional tornado outbreaks, Annual AGU Meeting, December 14 – 18, 2015, San Francisco, CA.

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5. Future Work

1) For our future work, we will complete our effort to developing the hybrid statistical-dynamic seasonal tornado outlook. The results shown in the attachment will be submitted for a publication.
2) The SSW tele-conference will resume in Februaty 2017.
3) Partnership Building: The PIs will continue to build relationships with partners in the federal government and academia to align research priorities effectively toward developing long-range severe weather outlooks.

Attachement: Seasonal Severe Weather Outlook (Experimental) for the US: March-May 2016

Recent violent and widespread tornado outbreaks in the US, such as occurred in the spring of 2011, have caused devastating societal impact with significant loss of life and property. The latest U.S. Natural Hazard Statistics reported that during 2005-2014 tornadoes claimed 1,100 lives in the U.S. (second only to heat-related deaths), and caused $21.7 billion in property and crop damages (http://www.nws.noaa.gov/om/hazstats.shtml). To help emergency managers, government officials, businesses and the public better prepare the resources needed to save lives and protect critical infrastructure, a seasonal severe weather (SSW) outlook is developed to expand and compliment the current severe weather outlooks at National Oceanic Atmospheric Administration (NOAA) beyond seven days. This SSW outlook is an experimental product of NOAA Atlantic Oceanographic and Meteorological and Laboratory (AOML). It is based on a hybrid statistical-dynamical prediction model, which is currently being used at NOAA Climate Prediction Center (CPC) as one of many prediction models and decision tools for CPC's SSW outlook (http://www.cpc.ncep.noaa.gov).

Springtime atmospheric environments and tornadogenesis in the US:
Over the central US east of the Rockies in spring, cold and dry upper-level air form the high latitudes collides with warm and moist lower-level air from the Gulf of Mexico at different altitudes. As a result, the atmosphere is unstable and the lower-level wind shear is very high providing favorable environments to form a supercell, which is known to be linked to tornadogenesis (Doswell et al. 2011).

The main goal of the SSW outlook:
Tornadogenesis is a mesoscale problem. Therefore, the SSW outlook cannot pinpoint exactly when, where and how many tornadoes may strike. Instead, the goal of the current SSW outlook is to predict in terms of probability which regions are more vulnerable to, or more likely to experience, a widespread outbreak of tornadoes.

Scientific basis of the SSW outlook:
Notable scientific advances have been made since 2011, a year of record-breaking spring tornado outbreaks in the U.S., toward expanding the severe weather outlook at NOAA beyond weather time scales. Among others, one recent study (Lee et al., 2016) showed that the dominant springtime El Niño-Southern Oscillation (ENSO) phases and the North Atlantic sea surface temperature tripole variability are linked to distinct and significant U.S. regional patterns of tornado outbreak risk. These changes in outbreak risk were shown to be largely consistent with remotely forced regional changes in the large-scale atmospheric processes conducive to tornado outbreaks.

Preparedness for severe weather events:
Damage and disasters from severe thunderstorms, tornadoes, and large hail can occur whether a season is active or relatively quiet, and it only takes one event impacting an area to cause a

disaster or potentially loss of life. Residents and businesses are urged to prepare for every storm season regardless of this outlook, as numerous tornadoes and hail events occur even in relatively quiet seasons. NOAA (http://www/noaa.gov) and FEMA (http://www.fema.gov) provide important storm preparedness information on their web sites.

SSW outlook summary

The SSW outlook for March-May (MAM) 2016 for each of the nine US climate regions (see Figure 3) is shown in Table 1. A summary of the SSW for the US regions prone to severe weather (Northeast, Northern Rockies, Ohio Valley, Southeast, South, Southwest and Upper Midwest) is given below:

- Above Normal number of tornado in the Northeast
- Normal to Above Normal number of tornado in the Southeast and Upper Midwest
- Below Normal to Normal number of tornado in the Ohio Valley, South and Southwest
- Below Normal number of tornado in the Northern Rockies

Table. 1 SSW outlook for spring (March-May) 2016 is shown for the nine U.S. climate regions. The three predictors, namely the two leading modes of MAM tropical Pacific SST anomalies and the leading mode of MAM North Atlantic SST anomalies, were obtained from CFSv2 (ICs: February 2016). Two sets of predictions based on 20-member ensemble mean, and 20-member ensemble mean plus one standard deviation are shown. The predictions are indicated by "Below", "Normal" and "Above", which mean that the predicted value is below the lower tercile, between the lower and upper terciles and above the upper tercile, respectively. Additionally, the probabilities of "Below", "Normal" and "Above" tornado activity, derived from the 20 member ensemble forecasts, are also shown.

US regions	Prob (%) of Below Normal	Prob (%) of Normal	Prob (%) of Above Normal	Ensemble Mean	Ensemble Mean + 1 STD
Northeast	0	5	95	Above	Above
Northern Rockies	95	5	0	Below	Below
Northwest	50	50	0	Normal	Normal
Ohio Valley	60	40	0	Below	Normal
Southeast	30	30	40	Normal	Above
South	75	20	5	Below	Normal
Southwest	60	40	0	Below	Normal
Upper Midwest	50	35	15	Normal	Above
West	0	100	0	Normal	Normal

SSW outlook discussion

The seasonal outlook of tornado density (EF1-EF5 tornadoes within 200 km radius) for March-May (MAM), March, April and May 2016 is shown in Figure 1. CFSv2 ensemble forecasts indicate that the current strong El Niño condition is very likely to persist throughout MAM 2016 with very high probability (Figure 2a). Strong and persistent El Niño events in spring tend to result in atmospheric conditions unfavorable for tornadogenesis across the US regions prone to severe weather. Therefore, tornado density is expected to be below normal over most of the US east of the Rockies. However, due to the southward shift of the mid-latitude jet and extratropical storm tracks, frequently occurring during strong and persistent El Niño events, the gulf coast regions and central Florida are expected to experience above normal tornado density. As observed in some of the strong and persistent El Niño events (e.g., 1982-1983 and 1997-1998), above normal condition is also expected in the Northeast.

One of the three predictors for tornado density used in the current SSW outlook is the North Atlantic SST tripole mode. A positive North Atlantic SST tripole mode (i.e., cold in the tropical North Atlantic, warm in the subtropical North Atlantic and cold in the subpolar North Atlantic) is known to be linked to a tornado outbreak in the US (Lee et al., 2016). CFSv2 ensemble forecasts indicate that a positive North Atlantic SST tripole mode is most likely with a very large spread of the ensemble members (Figure 2c). Therefore, there is some chance to have a very strongly positive North Atlantic SST tripole in MAM 2016. Mainly due to the large uncertainty in the strength of the North Atlantic SST tripole, there is some chance that Texas, Oklahoma and Kansas may experience above normal tornado density.

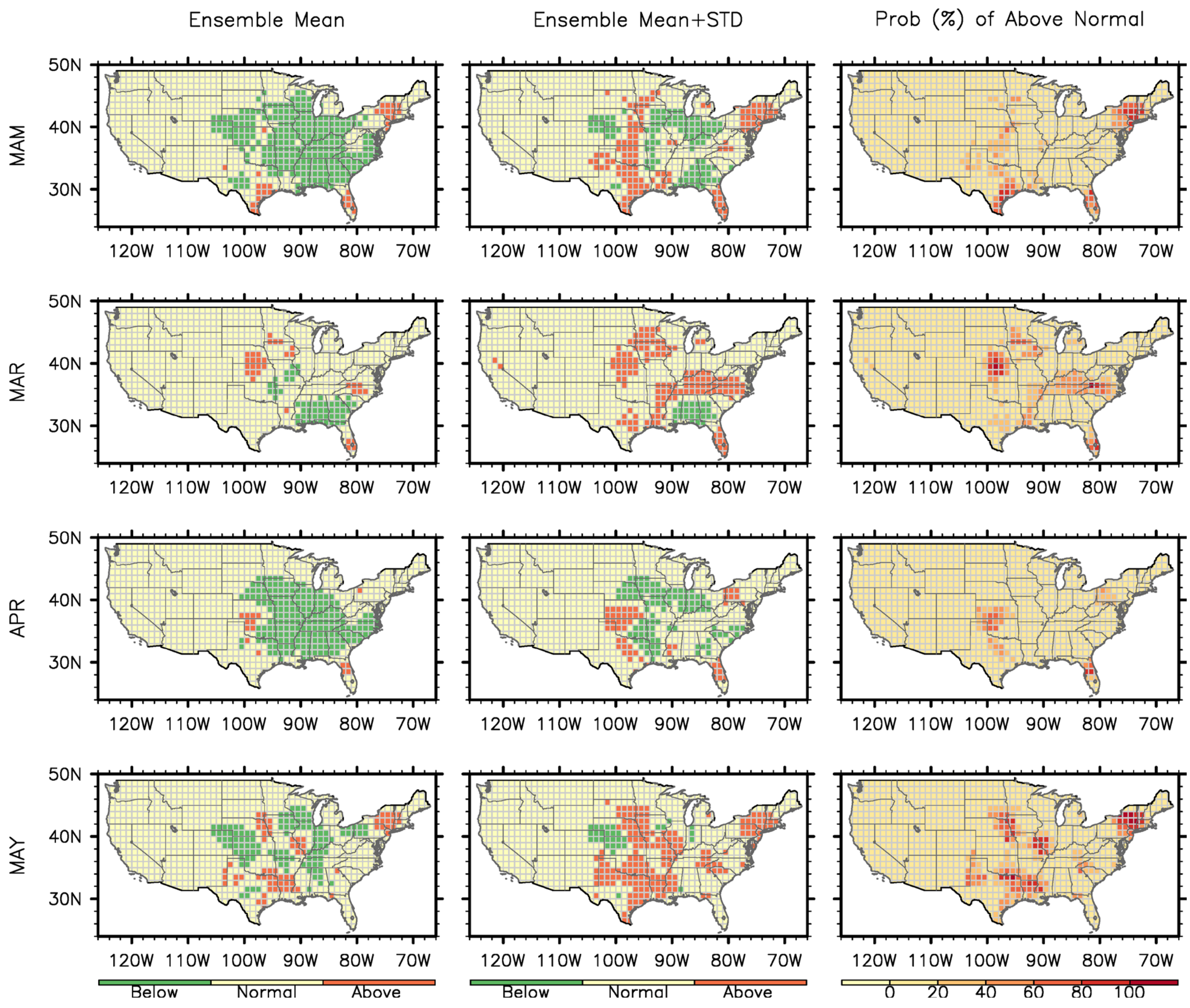

Figure 1. Hybrid statistical-dynamical prediction of tornado density (EF1-EF5 tornadoes within 200km radius) for (1st row) MAM, (2nd row) March, (3rd row) April and (4th row) May 2016. (left column) Ensemble mean, (mid column) ensemble mean + 1.0 standard deviation departure of ensemble members. A 1/3 tercile distribution is used to indicate below normal (green), normal (yellow) and above normal (dark orange) tornado density. (right column) The probability (%) of above normal tornado density derived from 20 ensemble members CFSv2 forecasts.

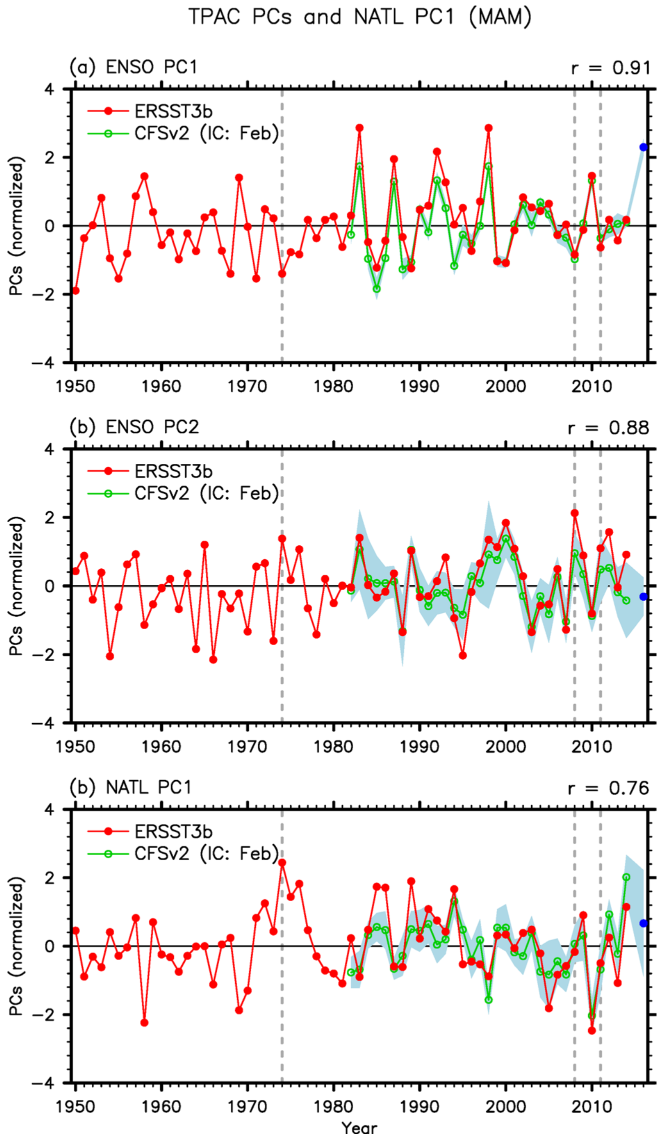

Figure 2. Three predictors derived from ERSST3b and CFSv2. (a) The 1st and (b) 2nd EOF modes of tropical pacific SST anomalies and (c) the 1st EOF modes of North Atlantic SST anomalies during March-May (Lee et al., 2014; 2016). The light blue shade indicates ensemble spread of CFSv2 forecasts (± 1 standard deviation). Partial linear regression in the context of multiple linear regression analysis is used with the three predictors to forecast tornado counts and tornado days for March-May.

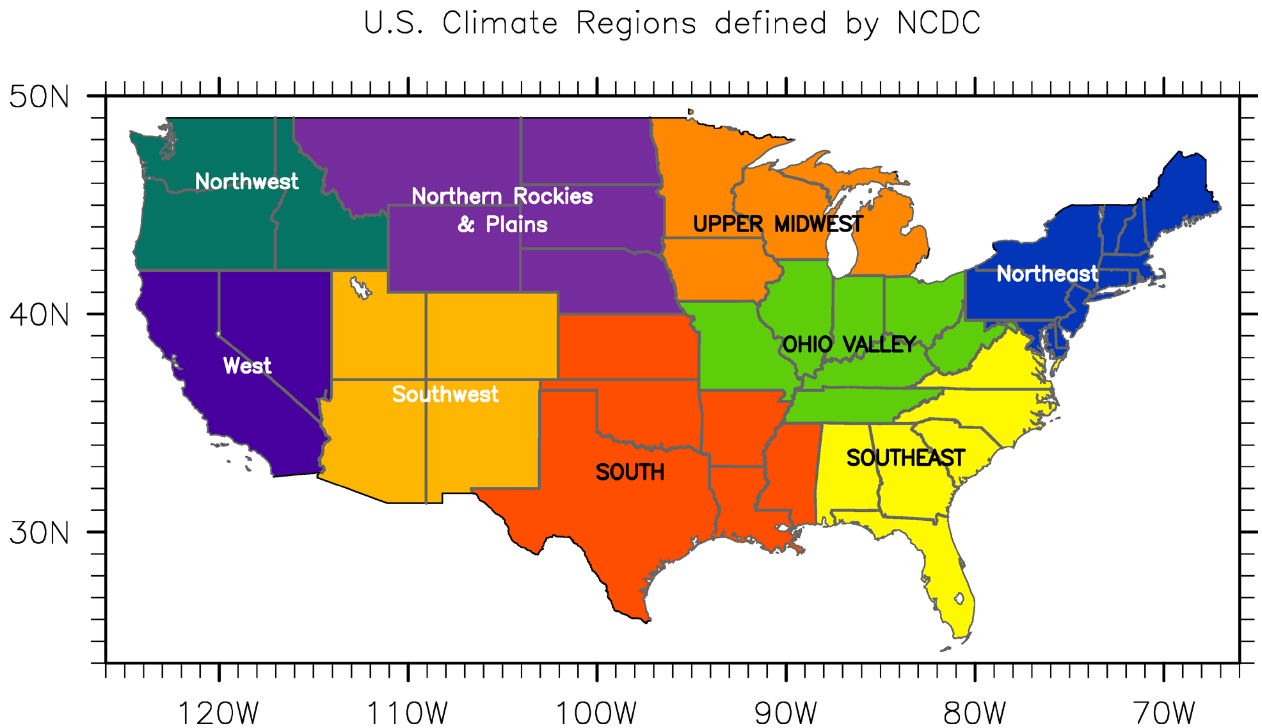

Figure 3. Nine U.S. climate regions defined by National Climate Data Center.

Prediction Tools

Seasonal tornado counts (EF1-EF5) within a 200km radius from each of 1°×1° grid points (tornado density) are predicted. The enhanced Fujita scale-0 (EF0) tornadoes are excluded in our analysis to avoid a spurious long-term trend in the severe weather database. To avoid double-counting, the location and EF-scale of each tornado are determined at the time when each tornado achieves its maximum EF-scale. The prediction is based on a hybrid statistical-dynamical model that uses CFSv2 ensemble forecasts of March-May SST anomalies. Three predictors are derived from the 1st and 2nd EOF modes of tropical pacific SST anomalies and the 1st EOF modes of North Atlantic SST anomalies (Lee et al. 2016). Partial linear regression in the context of multiple linear regression analysis is used with the three predictors to forecast tornado counts and tornado days for March-May.

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