VORTEX-SE
Science Assessment

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VORTEX-SE Scientific Steering Committee

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Abbreviations and Acronyms

AGL Above Ground Level height
CAM Convection-Allowing forecast Model
CAPE Convective Available Potential Energy
CF VORTEX-SE Community Forum
CIN Convective Inhibition, a thunderstorm forecast parameter
CM1 George Bryan Community Model, a research numerical atmospheric model
FACETs Forecasting a Continuum of Environmental Threats
GSL NOAA/OAR Global Systems Laboratory
HRRR High-Resolution Rapid Refresh forecast model
HSI Horizontal Shearing Instability, a proposed tornado formation mechanism
HSLC High-Shear, Low-CAPE, a description of atmospheric conditions associated with many Southeast U.S. tornadic storms
IWT Integrated Warning Team
LAOF Lower Atmospheric Observing Facility
LCL Lifting Condensation Level, a tornado forecast parameter
LTC Landfalling Tropical Cyclone
MH Mobile/Manufactured Home
MMH Mobile-Manufactured Housing
NOFO Notice of Funding Opportunity
OFAP Observing Facilities Advisory Panel
PBL Planetary Boundary Layer
PI Principal Investigator
PM Program Manager
PSL NOAA/OAR Physical Sciences Laboratory
QLCS Quasi-Linear Convective System, a contiguous area of storms and precipitation longer than it is wide
SBE Social, Behavioral, and Economic sciences
SRH Storm-Relative Helicity, a tornado forecast parameter
SSC Scientific Steering Committee
STP Significant Tornado Parameter
WSE Wind and Structural Engineering

1. Introduction to the September 2020 Update

VORTEX-SE is a research program focused on tornado issues of special concern in the southeastern United States. The overarching goal of VORTEX-SE is to reduce damage, injuries, and loss of life from tornadoes through improvements in understanding, forecasting and warning, and communicating risks in ways that support protective decision making. This includes understanding and, where possible, providing recommendations for how to mitigate key vulnerabilities to tornadoes in the southeast US.

Physical science and observational advances that can help improve operational forecasts and warnings are important contributors to reducing loss of life from tornadoes in the southeast U.S. Contributions from the Social, Behavioral and Economics (SBE) sciences and engineering are also critical in order to understand societal aspects of Southeast tornado risks and to help meteorological advances achieve their potential for benefiting society. Thus, VORTEX-SE spans a range of disciplines, including atmospheric science, SBE sciences, engineering, and operational meteorology.

VORTEX-SE began in 2015 when Congress appropriated special funds to NOAA for this research, and NSSL was chosen as the laboratory to lead the work. This program has been continued with annual special appropriations of around $5M each year since. The first grant competition occurred in 2015, with the first set of grants awarded late in FY2015. These were generally two-year grants, with third-year no-cost-extensions, and final reports received around December 2018. As of this writing, grant-supported research has been completed on the FY2015 and 2016 awards. The research from these first two funding years was relatively broad in nature but has provided a strong foundation upon which to build more focused research.

This assessment is the result of a collaboration between several groups. First, three CIMMS employees (Rasmussen, Sharpe, and Lyza; *ex officio* members of the VORTEX-SE Scientific Steering Committee) have been heavily involved in the initial draft because they have access to grant progress reports and hence are in a good position to summarize completed and (especially) ongoing research. It is their role, collaborating with grant investigators, to ensure that program research is accurately represented. The second group is the Scientific Steering Committee which has the overall responsibility of ensuring that this assessment represents the sense of the broader community. Finally, as noted herein, various grant investigators and other invited contributors have provided input.

The 2020 assessment is being produced to summarize and update the NOAA VORTEX-SE community, as well as the larger research community and funding agencies. The recommendations in this assessment should be viewed as an ~3-year roadmap. A more continuous process of informing the community, soliciting opinions and perspectives, and broader discussions will occur in the VORTEX-SE Community Forum[1]. All parties interested in working to mitigate the tornado risk in the Southeast are encouraged to participate. Further, the Community Forum contains significant details about ongoing and completed research that could not be fit into this assessment.

Every topic in this Science Assessment has a section describing "Needs" in Chapter 4, in which we assess the science needs from the perspective of “what research should be done to advance the topic toward application for societal benefit?” The range of assessed "readiness for

[1] You may contact Erik.Rasmussen@noaa.gov for permission to join.

application" is wide. In some areas, no societal benefit is possible until fundamental questions are answered, while in others, knowledge is almost ready for application. These levels of readiness are noted in the Needs sections where appropriate.

VORTEX-SE has a strong expectation for rapidly producing knowledge that can be put into practice to benefit society, consistent with the Congressional intent and the NOAA mission. As such, the program will continue to strongly encourage both physical and social science research that maintains a clear path to operations and life and property mitigation.

2. Physical Science Findings and Ongoing Research

2.1 Terrain and Roughness Influences on Tornadoes and Storms

a. Findings

The primary focus of VORTEX-SE sponsored research in the effects of terrain on the Southeast tornado problem has largely focused on the role of topographic features in modifying the near-storm environment. Much of this work has focused on the Sand Mountain plateau region in northeastern Alabama. Sand Mountain was highlighted prior to VORTEX-SE as an area where the local topography was thought to have a possible influence on the occurrence of tornadoes, notably a perceived (by both operational and research meteorologists in northern Alabama) higher probability of tornado formation atop the plateau than in the adjacent Tennessee/Sequatchie Valley.

Initial analysis began prior to VORTEX-SE, assessing the rate of tornadogenesis atop the combined Sand Mountain and Lookout Mountain plateau system and at surface observations both atop Sand Mountain, with an AWOS station at Albertville, AL (K8A0) and another at Scottsboro, AL (K4A6). The results of this analysis were presented in Lyza and Knupp (2018, hereafter LK18). A Getis-Ord local statistic (G_i*) analysis highlighted Sand Mountain as a statistically significant hotspot for tornadogenesis for the 25-y period from 1992-2016 for the region within 250 km of Sand and Lookout Mountains, while observations from K8A0 and K4A6 showed a tendency for stronger and more backed 10-m winds atop Sand Mountain at K8A0 than in the adjacent Tennessee Valley at K4A6. LK18 also hypothesized that the stability of the environment and the orientation of the low-level flow in the vicinity of the plateaus may explain the acceleration of flow observed in the surface data set atop Sand Mountain. Upstream Froude numbers from RUC/RAP soundings prior to Sand and Lookout Mountain tornado events showed a strong tendency for conditions favorable for the acceleration of low-level flow overtop the plateaus, potentially maximizing along the leeward slope of Sand Mountain in a standing wave.

The results presented in LK18 formed the basis for deployments in northeastern Alabama from Fall 2016 through Spring 2019, with a particular focus during the Spring 2017 field campaign. Observations gathered during these field activities are summarized in Lyza et al. (2020). Most notably, balloon soundings support lower LCL heights relative to ground level atop Sand Mountain than in the adjacent Tennessee Valley and higher values of 0-1 km SRH in environments when the background environment is favorable for tornadoes. Data from balloons, mobile radar, and Doppler wind lidar suggest the development of a downslope wind enhancement along the leeward slope of Sand Mountain, which can lead terrain-perpendicular winds increasing by as much as a factor of 2 to 3 along the slope compared to flow upstream.

Aside from observational efforts across northeastern Alabama, other VORTEX-SE-funded and completed research efforts have examined the role of terrain roughness in tornado frequency and occurrence patterns. Hua and Chavas (2019) found a statistically significant relationship between terrain roughness and tornadogenesis distribution across the state of Arkansas. Over length scales of 15-20 km, the probability of a tornado decreases by 11% by each 10-m increase in terrain roughness, with that effect magnified at smaller length scales. This effect was found to be consistent despite changes in population density over time.

Satrio et al. (2020) expanded upon large-eddy simulation work begun by Lewellen (2012) to investigate tornado interactions with different topographic features. Their results indicate that when a medium swirl tornado is crossing different topographic features, there is a tendency for the peak 10-m winds to be observed at elevation minima along the track, between hills or at the troughs of valleys. Secondary maxima in 10-m horizontal wind and the absolute maximum in w are observed on upslope track segments, induced by stronger subvortices than those observed in the control (non-terrain) simulation. Furthermore, consistent changes in translation and vortex size were observed, with leftward deflection, acceleration, and expansion of vortices upon ascending an obstacle and rightward deflection, deceleration, and contraction upon descent. These findings are yet to be corroborated through observations of actual tornadoes.

b. Ongoing Research

A number of projects regarding the potential roles of terrain and roughness on Southeast severe storm evolution are ongoing or nearing completion. Katona and Markowski (under review) utilized High-Resolution Rapid Refresh (HRRR) forecast model composites and CM1 (George Bryan's Community Model for simulating mesoscale atmospheric processes) simulations to further assess changes in thermodynamic and kinematic fields across Sand Mountain and the adjacent Tennessee/Sequatchie Valley region. Their experiments suggest that Lifting Condensation Level (LCL) heights do tend to be lower relative to ground level atop Sand Mountain than in the valley. On tornado-conducive days, HRRR composites of the Significant Tornado Parameter (STP) indicate higher values atop Sand Mountain than in the Tennessee Valley. The CM1 simulations indicate that on days with southerly low-level flow, Storm-Relative Helicity (SRH) tends to be higher atop Sand Mountain, while it tends to be higher in the Tennessee Valley on days with southwesterly low-level flow. Additionally, Convective Available Potential Energy (CAPE) was found to be slightly higher and Convective Inhibition (CIN) slightly lower atop Sand Mountain. However, it is unclear how any of these environmental variations may impact storms given the relatively small spatial and temporal scales of interaction between these terrain-induced effects and the parent storms.

Bryan et al. (2018) addressed the role of the plateaus in northeastern Alabama in storm-scale evolution. CM1 simulations using the 1800 UTC 27 April 2011 sounding at Birmingham, AL were performed both with and without terrain, to test the sensitivity of storm evolution to the underlying topography, and with rotated wind profiles to test sensitivity of storm interactions to the plateaus given the storm motion. Their results indicated that storms in the simulations with terrain had greater values 2-5 km integrated updraft helicity but lesser surface vertical vorticity than in the no-terrain simulations. However, these simulations were performed without PBL or surface drag parameterizations, which would not allow for the same effects documented in Lyza et al. (2020) or Katona and Markowski to be robustly tested for their impacts on storm evolution. Additionally, it is not clear that the sounding used really typifies the environments that are most conducive to tornadoes in the terrain of northeastern Alabama.

Work is also continuing on the role of terrain roughness on tornado climatology. Results from Biggerstaff et al. (2019, VORTEX-SE workshop) have shown little relationship between differential roughness of the land and tornadogenesis frequency. However, their results do indicate a relationship between terrain gradient sign and tornadogenesis. The favored gradients indicate decreasing elevation along a storm tracking from southwest to northeast (the most typical storm motion for tornadic storms in Alabama), so these results indicate a tendency for tornadogenesis to occur on downward slopes. Note that this study does not employ population bias controls as in the Hua and Chavas (2019) study.

Finally, early work by K. Lombardo indicates that Quasi-Linear Convective Systems (QLCS) are more intense both upwind and downwind of a mountain, and that near-surface flow in valleys ahead of a QLCS is channeled, all of which may lead to conditions more favorable for tornadogenesis.

2.2 Internal Storm Processes

a. Findings

1. Overlapping Tornado and Flash Flood Hazards (TORFF)

One particular focus understanding storm processes in the Southeast has been in events where flash flooding and tornadoes pose simultaneous, substantial threat to life and property (tornado/flash flood or TORFF events). While this overlay of hazards poses significant challenges to hazard messaging, an interplay also exists in the physical causes of these phenomena. Nielsen and Schumacher (2018) investigated the physical link between low-level wind shear and extreme rainfall rates. Environments with stronger low-level wind shear were found to be more conducive to extreme rainfall rates through the relationship between low-level wind shear and the development of low-level updrafts. Stronger low-level wind shear leads to more robust storm rotation and non-linear dynamic pressure perturbations, which in turn lead to stronger low-level updrafts despite near-surface stability. These stronger low-level updrafts lead to more water vapor being processed by a storm. Increased wind shear also leads to increased inflow into updrafts. The total increase of water vapor available to a storm through these dynamic effects is able to offset the low precipitation efficiency of supercells and lead to extreme precipitation rates and flash flooding threats.

To quantify the effects of rotation on extreme precipitation events through observations, Nielsen and Schumacher (2020a) analyzed extreme rainfall rate events (rates exceeding 75 mm hr^{-1}) over a 5-year period across the United States. Their results indicated that 41% of observed extreme precipitation events occurred in the vicinity of rotation. Events that occurred in the vicinity of rotation were largely concentrated along the Gulf Coast in the warm season, while events that occurred without rotation were observed in the presence of boundaries. Proximity to rotation was found to be an important contributor to extreme rainfall rates during Houston's 2016 Tax Day flood event (Nielsen and Schumacher 2020b).

2. QLCS Mesocyclone/Mesovortex and Tornado Development, Behavior, and Evolution

Conrad and Knupp (2019) investigated horizontal shearing instability (HSI) in two cold-season QLCS cases in northern Alabama using dual-Doppler analysis between the Hytop (KHTX) WSR-88D and the University of Alabama-Huntsville ARMOR radar. The first event was on 4 January 2015, when an EF1 tornado impacted the city of Albertville in northeast Alabama, atop Sand Mountain. The other event was on the evening of 28 November 2016, when a non-tornadic, largely sub-severe QLCS moved across the Tennessee Valley after producing wind damage in Mississippi. In both cases, the condition for HSI was met along the wind shift associated with the QLCS. In the 4 January case, the wind shift angle was found to be sharper than in the non-tornadic 28 November case. This case demonstrates that, while HSI could certainly contribute to mesovortex and tornado formation in High-Shear, Low-CAPE (HSLC) environments, the Rayleigh and Fjortoft instability criteria are still necessary but insufficient conditions for diagnosing HSI release and vortex development.

In a project aimed at gaining increasing understanding of vortex production in QLCS, with possible relevance to Southeast events, Lyza et al. (2017 and 2019) conducted a detailed assessment of the mesovortices and tornadoes associated with the second 30 June 2014 derecho in the Midwest. The 2017 study focused on the development and behavior of the 38 identified mesovortices, while the 2019 study focused on the assessment of a complex cluster of 18 tornadoes associated with a pair of mesovortices. In the 2017 study, no statistically significant differences could be determined between the characteristics of the tornadic and non-tornadic mesovortices, although there was a slight tendency for tornadic mesovortices to be longer-lived and featured slower translational speeds. The study did find evidence of complex behaviors among the mesovortices, including binary (Fujiwhara) interactions, mesovortex splitting, satellite mesovortices, and interactions between mesovortices that formed along the primary gust front with those that formed in a secondary convective band ahead of the primary line. The 2019 study showcased the utility of high-resolution satellite imagery in assessing EF1-EF2 tornado damage associated with the two most prolific vortices of the second derecho. The addition of over 500 points of satellite-derived information led to a total reanalysis of a complex tornado cluster in rural areas south of Chicago, where the breadth and accessibility of damage points led to an incomplete analysis after the initial surveys from the event were performed.

3. Development of Surface Vortices

Sherburn and Parker (2020) conducted CM1 simulations of HSLC convection to assess the formation of severe surface vortices in HSLC environments. The study found that surface vortex generation in HSLC environments began with development of a low-to-mid-level (500 m to 2 km AGL) vortex under a mid-level updraft up to 20 minutes prior to surface vortex genesis. This low-to-mid-level vortex helps intensify the low-level updraft through non-linear dynamic acceleration, which in turn increases low-level tilting and stretching, ultimately leading to intense surface vortex development. Higher values of environmental 0-1 km shear led to development of more numerous vortices, while steeper 0-3 km temperature lapse rates led to deeper, more intense vortex formation.

In work supported by VORTEX-SE to understand tornado formation from a basic science perspective, Dahl (2020) examined the “roll-up” of elongated regions of enhanced vertical vorticity into axisymmetric near-surface vortices in supercells utilizing an initial value approach in CM1 simulations. Genesis of axisymmetric near-surface vortices was shown to be predicated only on finite-amplitude inhomogeneities in the preexisting vortex path. Horizontal flow induced by the elliptical vortex patches themselves led to differential horizontal advection of vorticity, resulting in self-organization of the vorticity patches into axisymmetric near-surface vortices.

4. Relationship between Mesocyclone Diameter, Overshooting Top Extent, and Tornado Strength

Marion et al. (2019) assessed the use of overshooting top area (OTA), as estimated in GOES-16 longwave infrared data, in predicting tornado intensity. The underlying assumption was posed that OTA should be positively correlated to updraft area, which would then in turn be correlated to tornado intensity. Their results indicate a correlation between OTA and tornado intensity (R^2 = 0.54).

Sessa and Trapp (2020) tested the hypothesis developed in Trapp et al. (2017) that larger (wider) mesocyclones should lead to stronger tornadoes across a variety of both supercellular and QLCS tornado cases. For supercells, a strong statistical relationship (R^2 = 0.82) was found between pre-tornadic mesocyclone width and EF rating of the subsequent tornado. For QLCSs, the relationship is far weaker (R^2 = 0.37). The pre-tornadic mesocyclone width performed more consistently than pre-tornadic mesocyclone intensity (as defined by rotational velocity) as a predictor of tornado intensity.

5. Polarimetric Signatures Associated with Non-supercellular Tornadoes

Loeffler and Kumjian (2018) investigated differential reflectivity (Z_{DR}) and specific differential phase (K_{DP}) signatures associated with non-supercellular tornadoes within 60 km of a WSR-88D radar across 30 cases from 2013-2016. In these 30 cases, a separation between the maximum Z_{DR} and K_{DP} regions was observed, indicative of size sorting of hydrometeors. The separation distance was found to reach a peak near the time of the tornado report associated with the parent storm, with the separation between the Z_{DR} and K_{DP} maxima typically ranging between 3-4 km. A change in the separation angle relative to storm motion between the maxima was also observed, with separation angles tending to be more orthogonal to storm motion near the time of tornado report. Separation angles were also found to be more orthogonal to the storm motion vector as SRH increased when compared to RAP soundings using the observed storm motion for the SRH calculation.

b. Ongoing Research

1. QLCS Vortex Development

A pair of ongoing projects by Biggerstaff, and Wurman and Kosiba, are examining the generation of vortices with the 3 April 2018 QLCS across northern Alabama. Dual-Doppler syntheses between two pairs of mobile Doppler radars in Biggerstaff's study show an evolutionary process where several convective downbursts led to a large-scale bowing of the line and significant wind damage. The worst damage found in post-event surveys aligned with dual-Doppler derived regions of strong vertical vorticity, consistent with mesovortices and likely tornado occurrence. This study may provide insights as to how higher spatiotemporal resolution Doppler data can better identify localized enhanced damage potential, compared to WSR-88D operational data.

Analyses by Kosiba and Wurman indicate that the release of HSI in the 3 April 2018 event was supported by dual-Doppler analyses, providing a potential mechanism for the generation of vortices, but the release of HSI is common in these systems and, alone, likely is not a sufficient mechanism for development of tornado-strength vortices. The mechanism for the genesis of tornado-strength vortices in QLCSs remains unknown and will be a focus of the PERiLS project.

In addition to 3 April 2018, both projects are also analyzing other QLCS cases, including 27 March 2017, 30 April 2017, 28 March 2018, and 14 April 2018.

An NSF-supported project is especially relevant to this topic. On 12 April 2020 an EF-3 tornado struck the Monroe, LA area, and was observed at high resolution by the University of Louisiana-Monroe S-band dual-polarization Doppler radar, as well as other instruments. An NSF-RAPID grant is supporting PI Murphy to explore the tornadogenesis process in this QLCS event.

Of special note, the Biggerstaff project is also examining the 14 April 2018 QLCS that produced tornadic damage in northwest Louisiana. This study is using multiple Doppler data sources. The mesovortices that were associated with tornadoes were persistent over time scales of more than one hour and tracks of more than 100 km length. Understanding how these mesovortices maintain intensity, and thus define more persistent areas of threat, may motivate further research into whether long-lived mesovortices are a common feature and potentially a useful tornado situational awareness tool.

2. Microphysics, Electrification, Cold Pools, and Draft Structure

Using disdrometer observations from the VORTEX-SE 2016 and 2017 field campaigns, the Advanced Regional Prediction System (ARPS) model, and associated EnKF radar data assimilation system, Dawson and collaborators are examining the role of precipitation physics in influencing cold pool characteristics, and hence tornado potential, in Southeast U.S. QLCSs. Preliminary results show that ARPS with the NSSL triple-moment microphysics scheme (NSSL-3M) can successfully simulate disdrometer-observed drop size distributions in simulations of the 31 March 2016 (supercells) and 30 April 2017 (tornadic QLCS) cases.. If the model is faithfully reproducing surface precipitation and cold pool character, it should prove useful to gain understanding into the role of the cold pools in tornado formation.

Related work by Weiss and collaborators is examining the differences in cold pools, observed with StickNet instruments, in tornadic and non-tornadic storms observed by VORTEX-SE. Two approaches were taken for these measurements, a fixed array of stations that remained in place for the duration of the project (the “StesoNet”, covering a ~10,000 km^2 expanse on northern AL and southern TN) and short-fused deployments during specific IOPs, usually embedded within the StesoNet domain. A recent analysis of 2016 and 2017 storm intercepts (McDonald and Weiss 2020; in revision) highlights the following principal conclusions: 1) The horizontal virtual potential temperature gradient magnitude has some skill in discriminating between tornadic and nontornadic portions of the lead convective line, 2) cold pool deficit magnitudes vary according to storm mode (linear systems, the strongest), and 3) no clear difference was found between deficits of virtual and equivalent potential temperature for tornadic vs. non-tornadic cells/line segments. The period of study by McDonald and Weiss (2020) did not feature any samples of cold pools associated with significant tornadoes. It is anticipated that forthcoming projects, such as PERiLS, will provide the opportunity to observe a broader spectrum of storms and generalize, particularly, the association of virtual potential temperature gradient with tornado development.

For the 27 March and 30 April 2017 VORTEX-SE IOPs, investigators Marquis, Kosiba, and Wurman conducted trajectory analyses and coupled these with limited sounding and surface mesonet data to diagnose the origins of downdraft air along the leading edge of the QLCSs. They found that the near-surface air associated with vorticity maximum in the QLCSs originated from different altitudes than the overall air comprising system-scale downdrafts (Marquis et al. 2018). Using hydrometeor classifications derived from dual-pol data, heavy rain and hail were present just above the trajectory height (> 1 km), suggesting significant hydrometeor loading could be present. Additionally, since no hail/graupel were observed at the surface, melting between 1.25 km and ground level occurred. These results suggest that sub-system-scale features/vortices may result from different processes and/or originate closer to the surface than system-scale features/downdrafts. Identifying these near-surface mechanisms may be particularly important for understanding which vortices have the potential to intensify to tornado strength. The targeted and dense set of PERiLS observations will help capture along-line features and environmental variabilities. This study also looked at the effects of terrain in the dual-Doppler wind retrievals, and found little impact on the magnitude of the vertical winds, but radar observations very close to the ground in terrain were lacking.

C. Nixon (2019, TTU MS thesis with Bruning) examined lightning and modeled environmental data in and near 19 tornadic QLCSs nationwide during all seasons from Apr 2017 - Dec 2018. While QLCSs typically exhibit quasi-homogeneous, extensive regions of moderate to high reflectivity along the line, GLM observations showed more individuated cells that were defined by a persistent trackable maximum in flash extent density over hour-long time-scales, consistent with the presence of a longer-lived mixed phase updraft that could drive persistent electrification. Within these cells there was good correlation (R^2 = 0.76) among cell-mean-lifetime GLM flash extent density (FED), MLCAPE, and 0-3 bulk km shear (3BS). In a line-relative sense, a tendency was observed toward greater MLCAPE and FED to the right of the QLCS apex, and a slight tendency to maximize 3BS to the left of the apex. No obvious association with likelihood of tornadogenesis was found. On the other hand, flash rate fluctuations (measured by the lightning jump sigma magnitude) showed little correlation to the mesoscale environment, suggesting such variations are driven by internal storm processes or environmental variability at scales smaller than meso-beta. These findings have motivated a comparison of StickNet thermodynamics and winds to variability in LMA flash extent density as a function of distance and time from each StickNet location in the 2016 and 2017 field campaign datasets. This work by T. Welty and Bruning is ongoing, and will use a principal components approach to study this multi-parameter dataset with respect to finer-scale warm-sector and cold pool heterogeneity observed by the StickNets.

Building on these ongoing projects, another project begun in 2019 is attempting an even more holistic synthesis of the microphysical and dynamical processes and their consequences in Southeast U.S convective systems. This project is a collaboration between Purdue University (Tanamachi, lead PI) and Texas Tech University (Bruning, lead PI). The project is seeking to understand the relationship between storm electrification, microphysics and drafts, cold pool character, and tornado formation using a mixture of observation and modeling studies.

2.3 Storm Environments, Storm-Environment Interaction, and the Planetary Boundary Layer

Since the beginning of VORTEX-SE, there have been assertions and indications that significant inhomogeneities exist in the near-storm environments of potentially tornadic storms, and that these are poorly sampled, if at all, in existing observing systems. There has also been an interest among several groups of researchers in characterizing Planetary Boundary Layer (PBL) processes, and representing them in numerical prediction models with greater fidelity. Further, forecaster impressions from the various VORTEX-SE field campaigns are that low-level stratification is one possible key to anticipating tornado potential, and hence this stratification needs to be observed and forecast with much greater reliability.

a. Findings

1. Near-Storm PBL Evolution

Coleman et al. (2018) evaluated the evolution of the near-storm environment in proximity to a significant (EF2) tornado in the Birmingham, AL, area on 1 March 2016. The tornado occurred only 30 km northwest of the Birmingham NWS office (BMX) and 41 minutes after the release of the 0000 UTC 2 March radiosonde. The radiosonde recorded an extremely low surface-based convective available potential energy (SBCAPE) of 11 J kg^{-1} and no mixed-layer CAPE (MLCAPE). Surface observations from co-op and personal weather stations across the Birmingham area indicated a narrow axis of higher surface dewpoint located just north of the BMX office, in the area where the EF2 tornado occurred. When adjusted for a representative surface condition from this axis area, the BMX sounding SBCAPE value increased from 11 J kg^{-1} to 869 J kg^{-1}. This case serves as an example of substantial, meaningful boundary layer heterogeneity on a meso-gamma temporal and spatial scale.

2. Impacts of Additional Soundings on CAM Data Assimilation

During the Meso18-19 Intensive Observing Periods (IOP), radiosondes were launched every 6 hours by the Weather Forecast Offices (WFO) in the Southeast. Furthermore, several research groups launched radiosondes every 6 hours at locations between the WFOs. Over 1700 soundings were contributed to the VORTEX-SE data archive through this effort. The objective was to determine if these extra radiosondes, when assimilated, would lead to improved initial conditions on the distribution of temperature, moisture and winds in and above the boundary layer, and if that would result in improved short-term forecasts of convection in the VORTEX-SE domain. NOAA/OAR Global Systems Lab (GSL) staff tested this hypothesis (i.e., namely that the additional radiosonde data would lead to improved short-term forecasts) using the 3km High Resolution Rapid Refresh (HRRR) model. They used version 4 of the model, which has the improved storm-scale ensemble data assimilation system called HRRRDAS, for these tests. [HRRRv4 should become the operational version of HRRR at NCEP in December 2020; the code had already been frozen before these data assimilation (DA) tests were conducted.] Two DA runs were conducted: a control experiment that uses the standard data assimilated by the HRRR operationally (i.e., twice daily sondes at the WFOs, surface met from ASOS stations, AMDAR aircraft profiles, radar reflectivity and radial wind data, etc), and the experimental run that included the control observations plus the additional radiosonde data. IOPs 3, 4, 5, 6, 7, and 8 were analyzed. A wide range of objective and subjective evaluations were performed, and the impact of these additional radiosonde data was extremely slight to negligible during all 6 of these IOPs. It is possible that the information from these special soundings was not sufficient, compared to the vast number of other assimilated observations, to influence the forecasts. It is also possible that improved data assimilation methods, especially those that are multi-scale, might have resulted in an improved forecast; however, the goal of this test was to evaluate the impact on the operational HRRR. It should be noted, however, that the special soundings in Meso18-19 were useful to operational forecasters for better understanding the environmental state.

The findings thus far regarding data assimilation and the correct mix of observations to improve numerical forecasts would suggest that a great deal of work remains to be done in this area, and that the scope of this research is well beyond what can be accomplished through a program the size of VORTEX-SE. However, VORTEX-SE research should be conducted in such a way that special observations can be valuable to larger external projects focused on data assimilation.

3. PBL

Improved profiles of temperature, humidity, and wind are especially important in the Southeast U.S. where CAPE tends to be small, and hence very sensitive to low-level variations in temperature and humidity, and wind shear tends to be very large. However, profiling is complicated by the typical presence of low clouds and precipitation in the antecedent environments. Therefore VORTEX-SE has supported work to identify the optimal mix of profiling approaches in these environments.

As a preliminary step toward characterizing PBL height evolution in the Southeast U.S. prestorm environment, Tanamachi and collaborators (2019) used the vertically pointing, University of Massachusetts S-band FMCW radar in Spring 2016 and Spring 2017 to monitor the PBL on time scales on the order of 30 sec for 6 to 7 weeks per season. Observations from this radar comprise Doppler spectral profiles as well as derived moments of reflectivity, radial (vertical) velocity, spectrum width, and signal-to-noise-ratio. At S-band, in the absence of precipitation, the top of the convective boundary layer is easily detected in clear air as a prominent layer of turbulent Bragg scatter. To ease automated detection of this PBL height marker, it was necessary to censor observations of precipitation from these data. UMass FMCW observations were algorithmically classified into precipitation, non-precipitation, and no-data categories. To the resulting non-precipitation observations, an EKF-based algorithm is used to automatically determine the PBL height for all 14 weeks' worth of UMass FMCW observations. This work is ongoing at the time of this writing; an example can be found in Tanamachi et al. (2019). Furthermore, the Doppler spectra and moments data from observations classified as precipitation are being used by Prof. Daniel Dawson and his students to ascertain microphysical processes (e.g., size sorting, evaporation, and melting.) in storms observed by UMass FMCW and a collocated portable disdrometer. This work is also ongoing at the time of this writing.

VORTEX-SE has also supported work at NOAA/OAR/PSL as well as NSSL to develop and evaluate thermodynamic profiling, under the assumption that more frequent profiles will improve human and numerical forecasts in the Southeast. Thermodynamic profiles can be retrieved from Atmospheric Emitted Radiance Interferometers (AERIs; Turner and Löhnert JAMC 2014; Turner and Blumberg JSTARS 2019), which are included in the NSSL-OU CLAMPS facilities (Wagner et al. BAMS 2019). However, the vertical resolution of the temperature and humidity profiles coarsens with height above the instrument, and thus the retrieved profiles are generally unable to capture inversions at the top of the CBL. NOAA's Physical Sciences Laboratory (PSL) deployed radar wind profilers (RWP) with radio acoustic sounding systems (RASS) during the spring 2020 VORTEX-SE campaign. The RASS is an active remote sensing system that is able to provide partial profiles of potential temperature. We have been working on modifying the AERI retrieval so that the solution uses both AERI and RASS input, and the retrieved solution satisfies the observations from both instruments. The inclusion of the RASS virtual temperature profile, which starts at approximately 300 m and ends below 2.5 km, into the retrieval enables the algorithm to more accurately capture the elevated inversion at the top of the convective boundary layer, whereas the AERI-only retrieval smooths through that elevated inversion. Furthermore, not only does the AERI+RASS retrieval better capture the elevated inversion but that improved temperature profile results in a better retrieved water vapor profile that better represents the mixing in the entire convective boundary layer. We are performing similar work combining RASS with microwave radiometer (MWR) data; a paper on this work is currently being drafted. These results have encouraged PSL to purchase two AERI-like instruments (called ASSISTs), which can be co-deployed with RWP-RASS systems in future VORTEX-SE field campaigns.

VORTEX-SE has supported UAV work at the NOAA/OAR/ARL Atmospheric Turbulence and Diffusion Division laboratory at Oak Ridge. This work has focused on evaluating various copter UAVs for vertical soundings, as well as strategies to use UAVs to estimate surface fluxes. The UAV work at ATDD and a number of other organizations is showing promise for use in routine low-level soundings.

In a recently completed study, Markowski and collaborators (2019) showed, using VORTEX-SE Doppler lidar and profiler observations, that surface layer wind profiles often differed significantly from the profiles predicted by Monin-Obuhkov Similarity Theory. This was especially true on active weather days. This theory forms the basis for most surface layer treatments in numerical models. Thus this work will be useful for motivating re-evaluation of these treatments in future efforts to improve the simulation and forecast models.

b. Ongoing

VORTEX-SE is supporting a project in NSSL, supervised by Mike Coniglio, to refine ideas concerning the role of the environment in QLCS character. The primary goal is to critically evaluate the "three-ingredients" method for forecasting QLCS mesovortex-genesis (Schaumann and Przybylinkski 2012). These ingredients are 1) a portion of a QLCS in which the system cold pool and ambient low-level shear are nearly balanced or slightly shear dominant, 2) where 0-3 km line-normal bulk shear magnitudes are equal to or greater than 15 m s^{-1} , and 3) where a rear-inflow jet or enhanced outflow causes a surge or bow in the line. The first ingredient refers to the theory that attributes a strong forced updraft to a "balance" between cold-pool-generated horizontal vorticity and the horizontal vorticity of the opposite sign in the ambient environment (Rotunno et al. 1988, Weisman and Rotunno 2004).

Recent studies find that the processes that may generate a QLCS mesovortex are quite varied and may include tilting and stretching of frictionally-induced vorticity, processes similar to the generation of mesocyclones in supercells, or from combinations of all of the above processes (e.g. Schenkman et al. 2012, Xu et al. 2015,a,b, Flournoy and Coniglio 2019). In particular, the low-level wind profiles in some QLCS events appear to have sub-critical line-normal wind shear from the three-ingredients perspective.

To explore environmental controls on QLCS mesovortices (and tornado potential), radiosonde observations in proximity to QLCSs that were taken during past field programs, including from Meso18-19, will be collected and analyzed in relation to internal characteristics of the QLCS revealed by nearby WSR-88D observations (and from research radars when available). These observations will be supplemented with Doppler wind lidar (or research radar) observations of the vertical wind profile retrieved using the VAD technique when available to explore the typical variability of the wind shear at various distances from the QLCS. The goal is to identify scenarios when the three-ingredients method may not identify a QLCS mesovortex/tornado threat and to develop a set of recommendations to forecasters in these scenarios.

A project supported by the National Science Foundation and led by Ming Xue at the University of Oklahoma will be investigating the storm/environment interactions using the 2018 observations collected by the NOAA P-3 (dual Tail Doppler Radars, in situ state, and downward-pointing Raman lidar). These analyses will be combined with ensemble mesoscale model simulations that are aimed at representing the environments of the observed tornadic storms. This project could produce new understanding about inhomogeneities in flow, temperature, and humidity near tornadic storms, and the role of the inhomogeneities in modulating tornado potential.

VORTEX-SE has also supported NOAA/OAR/PSL in the development of a radar profiling system with a Radio Acoustic Sounding System (RASS) modified to function in environments with large low-level wind speeds. Wind can adversely impact RASS by advecting the acoustic signal downstream. The demonstration system has mitigated this issue by placing the acoustic sources upwind of the receiving antenna. This approach appears promising for routine profiling of temperature (not humidity) and wind in the Southeast.

VORTEX-SE is evaluating the idea that high-resolution Velocity-Azimuth Display (VAD) data will be useful for assessing the evolution of tornado potential in the environments of Southeast storms. Kosiba and collaborators have examined VAD-derived wind profiles from the various VORTEX-SE radars during the 2017 and 2018 seasons and compared these to radiosonde winds. VAD analyses from SR2, SR1 and MAX were used to construct hodographs ahead of the QLCS . Both low-level and deep-layer shear were strong and the VAD profiles derived from the three radars were in good agreement. We will compare the VAD analyses to sounding wind data and calculate shear, helicity, storm motion, and other parameters. These will be compared to storm structure, including sub-feature structures, both from dual- and single-Doppler data, throughout the evolution of the QLCS. It is anticipated the higher temporal resolution VADs will yield more insight into the (wind) environment.

A new grant has been made by the Weather Program Office to PSL. This grant spans a number of issues relevant to VORTEX-SE, including PBL processes. The abstract of the grant proposal is as follows:

> Forecasting the timing and location of convection and attendant precipitation in the southeast U.S. is critically dependent on proper simulation of the planetary boundary layer (PBL) evolution and the microphysical parameterization used by the forecast model. The difficulties in forecasting U.S. convective precipitation are shared by midlatitudes, subtropics, and tropics alike because this precipitation grows upscale from the boundary layer through convective processes. This study aims to address NOAA's Precipitation Prediction Grand Challenge by evaluating the ability of the NOAA High Resolution Rapid Refresh (HRRR) and Global Forecast System Finite-Volume Cubed-Sphere Dynamical Core (GFS-FV3) models to properly simulate the PBL and resulting convective and precipitation processes, with the goal of identifying shortcomings and areas for model improvement. The proposed effort will leverage a number of assets already set to be deployed for the Verification of the Origins of Rotation in Tornadoes Experiment-Southeast (VORTEX-SE) in Alabama and surrounding areas. VORTEX-SE is focused primarily on quasi-linear convective systems (QLCS) and non-supercell tornadic thunderstorms. We propose to augment VORTEX-SE by deploying additional instrumentation to properly characterize precipitation microphysics and the PBL. The proposal takes advantage of the Physical Sciences Laboratory's (PSL's) long history in deploying, maintaining, and analyzing observations to evaluate NWP models in terms of quantitative precipitation forecasts. This includes vertically-profiling and surface instrumentation to retrieve drop size distribution (DSD) characteristics in precipitation and to diagnose PBL structure. For this one-year project, we will evaluate the observations in comparison with model simulations of precipitation and the PBL. This analysis will

aim toward identifying more detailed science questions that could be addressed in subsequent years.

2.4 Climatology

a. Findings

1. Tornado Event Climatologies

Anderson-Frey et al. (2018) analyzed the near-storm environments of 14,732 tornadoes across the United States from 2003-2015. Tornadoes were classified by event mode (isolated tornadoes vs. tornadoes that were part of an outbreak), by parent storm mode (e.g. QLCS vs. right-moving supercell), by season, and by region. The near-storm environments were assessed using SPC's RUC/RAP sounding climatology as well as two-dimensional self-organizing maps (SOMs) to assess the variation of atmospheric parameters relative to tornado occurrence. Tornado outbreaks were most prevalent in the spring months. Outbreak tornadoes were associated with higher 0-1 km SRH, 0-6 km BWD, and lower ML LCL heights. In the Southeast, MLCAPE was also a discriminator between outbreak and isolated tornado events, with outbreak tornadoes featuring higher MLCAPE values. The SOMs reveal that, for modes with similar STP magnitudes, the STP maximum tends to be located east of a tornado event in the Plains and Midwest and northwest of an tornado event in the Southeast. Outbreak tornadoes are more common in the Southeast (42% of outbreak tornadoes) than in the Great Plains (24% of outbreak tornadoes), while isolated tornado events are more common in the Plains (34% of isolated tornadoes) than in the Southeast (25% of isolated tornadoes). Nocturnal tornadoes comprised a larger proportion of outbreak tornadoes (26%) than of isolated tornadoes (11%). Tornadoes in outbreaks were more frequently deadly than isolated tornadoes, with 6% of outbreak tornadoes producing fatalities as opposed to 1% of isolated tornadoes. Outbreak tornadoes featured a higher probability of detection (POD; 80%) than isolated tornadoes (59%), with isolated tornadoes in higher STP environments having a higher POD than those in lower STP environments.

Further work by Anderson-Frey et al. (2019) focused on the environments of Southeast U.S. tornadoes. Southeast environments were characterized by lower MLCAPE and MLLCL heights and higher values of 0-1 km SRH and 0-6 km BWD than the rest of the CONUS. STP tends to peak during Spring (MAM) and overnight events. In HSLC cases, increased EF ratings are associated with higher values of 0-1 km SRH and 0-6 km BWD, with little distinction in MLCAPE and MLLCL values from non-tornadic or weak-tornadic cases. The POD for Southeast tornadoes (71.5%) is slightly higher than the national average (65.6%), but the FAR is also higher than the national average (78.6% in the Southeast against 75.6% nationally). There was no discernable difference in POD or FAR between HSLC and all tornadic events in the Southeast. EF0-EF1 tornadoes saw the lowest POD (67.6%), but only 0.6% produced fatalities. 16.5% of EF2+ tornadoes produced fatalities, but were warned 86.9% of the time, and violent EF4+ tornadoes killed more than half the time but featured a 100% POD.

Childs et al. (2018) performed an analysis of cold-season (November-February) tornado environmental climatology across the United States. Cold-season tornado activity was found to be most common along the lower Mississippi River valley and across the Southeast, with decreasing incidence of cold-season tornadoes farther west. Increased cold-season tornado activity tends to be associated with higher 500 hPa geopotential heights in the eastern United States and lower corresponding heights in the northern Atlantic, typical of a positive Arctic oscillation (AO) phase. A dipole of sea-surface temperatures (SSTs) in the Gulf of Mexico is also evident, with positive SST anomalies in the western Gulf and negative SST anomalies in the eastern Gulf during active cold seasons. The cause of this dipole is unclear, but the dipole appears to promote higher precipitable water and surface dew point values across the Mississippi Valley and Southeast. Cold season tornado activity also appears to follow a 3-7 year cycle, mimicking the time scale of the El Nino-Southern Oscillation (ENSO), with La Nina ENSO phase being more favorable for cold-season tornado activity than El Nino or ENSO neutral phases. The most active cold seasons featured an increased number of observations of MLCAPE >750 J kg^{-1} with >30 m s^{-1} 0-6 km bulk wind difference, as well as steeper 700-500 mb temperature lapse rates. Cold season events are characterized by synoptic patterns featuring a trough over the western United States, ridging along the East Coast, and a jet streak centered over the central Plains. Both discrete and linear storm modes are common in cold-season tornado events, but discrete cells tend to produce stronger, deadlier tornadoes.

2. Forecast Performance

A study by Herman et al. (2018) examined the performance of SPC convective outlooks across the United States. Day 1 convective outlooks were examined over an 8-year period from January 2009-December 2016, and Day 2/3 outlooks were examined over a period from September 2012-December 2016. During the Day 1 forecast period, the best skill was exhibited in severe wind forecasts, followed by hail and tornadoes. For significant severe forecasts, the trend was reversed, with significant tornadoes showing the most skill, followed by significant severe hail and wind. The most active years featured the best forecasts, and spring and late autumn featured the most skillful forecasts. The least skill was exhibited in low shear and very high shear/very low CAPE environments. Overall, forecasts showed the most skill in the northern and eastern U.S. and the least skill in the southern and western U.S. Day 1 tornado and Day 2 and 3 outlooks displayed an under-forecast of threats, while forecasts were well-calibrated to Day 1 wind and hail events.

b. Ongoing Research

Ongoing work by Jeff Trapp is currently focused on relating mesocyclone size to environmental variables. The analysis compares pre-tornadic mesocyclone diameters to numerous thermodynamic and kinematic variables assessed by storm mode and meteorological season. Preliminary results indicate that the strongest relationship between the environment and pre-tornadic mesocyclone diameter exists for CAPE and other thermodynamic variables in meteorological spring (March-April-May), with higher values of CAPE corresponding to larger pre-tornadic mesocyclones.

Cameron Homeyer and collaborators (in non-VORTEX-SE-funded work) have analyzed systematic differences in radar-derived kinematic and microphysical variables between nontornadic, tornadic, and pre-tornadic supercells. The analysis applies a probability-matched composite mean technique to hundreds of supercells sampled in Homeyer's GridRad dataset. Mesocyclones are found to be much more vertically aligned during and 20 min preceding tornadogenesis than in nontornadic supercells. Similarly, the low-to-mid-level differential radar reflectivity dipole is oriented differently in tornadic supercells. Several other systematic differences are found that could be exploited by forecasters during tornado warning operations, either directly or via automated radar algorithms. One potential extension of this work is to stratify the analysis so as to identify any differences in tornadogenesis markers/precursors between geographical regions (e.g., SE vs. Plains) or environmental regimes (e.g., HSLC vs. HSHC).

2.5 Tornadoes in the Context of the Natural and Built Environment

a. Findings

VORTEX-SE research on tornadoes in the context of the natural and built environment has largely focused on two subjects: (1) utilizing tree damage to estimate tornado characteristics and intensity and (2) assessing failure of structures in tornadoes.

Two methods of estimating tornado intensity through tree damage have been investigated with support from VORTEX-SE because improved damage characterization will be important to future Southeast tornado research. The methodology developed in Godfrey and Peterson (2017) estimates the maximum 3-s gust associated with the percentage of fallen trees within a 100 m x 100 m area based on statistical wind resistance modeling. While the study shows significant potential in tree damage variability due to terrain effects, soil properties, and tree species resistance differences, it serves as a proof-of-concept toward developing a widely applicable method for estimating tornado intensity through tree falls in a wide variety of terrain. This methodology is serving as a baseline for development of new tree damage indicators (DIs) for the Enhanced Fujita Scale. Environment and Climate Change Canada (ECCC) has already developed an EF scale DI for tree fall fraction, and a similar DI is currently under development in the American Society of Civil Engineers (ASCE) EF scale standard subcommittee in the U.S.

The other methodology for estimating tornado intensity by analyzing tree damage that has been a focus of VORTEX-SE funded research is developed in Rhee and Lombardo (2018). This method builds off of a methodology developed by Lombardo et al. (2015) that utilizes a Rankine vortex model to estimate the horizontal wind speed profile associated with a pattern of observed tree damage. This method requires a transect of tree falls normal to the forward motion vector of the vortex, which is then compared to modeled transects of tree fall vectors assuming that the trees impacted by the tornado would fail (fall) at a uniform horizontal wind speed. The Rhee and Lombardo study expands on this methodology by accounting for limited asymmetry of the vortex and by applying the methodology to soybean crop damage in an Illinois tornado case. This method, however, continues to be limited by the effects of topography on the pattern of tree falls, and still does not account for multiple-vortex tornado structure.

VORTEX-SE has sponsored research toward using aerial imagery of tree damage to characterize certain aspects of tornado evolution. Cannon et al. (2016) employed a supervised classification scheme to assess damage severity from aerial imagery gathered in the wake of a pair of tornadoes from 27 April 2011 and compared the damage severity to underlying topographic features. Their findings suggest a tendency for damage severity to decrease as tornadoes ascend terrain features and to increase upon descent, with this behavior most notable on shallow slopes. Zenoble and Peterson (2017) used aerial imagery of 50 tornado tracks in forested areas to characterize the variability of damage along each track. Their findings indicate that damage width can vary substantially along short distances of a tornado track, leading to major differences between track characteristics for tornadoes assessed using aerial imagery versus strictly using ground survey information. However, the aerial imagery is often very limited in detecting damage of EF0 intensity, which can lead to actual tornado widths being over 200% greater than those analyzed by aerial imagery.

Further research has been conducted on the wind loads that lead to various degrees of damage in tornadoes. Roueche et al. (2017) developed empirical fragility curves using tree fall modeling of the 22 May 2011 Joplin, MO, tornado for single-family homes in both open and suburban (sheltered) exposures and compared those curves to curves developed in hurricane winds. In suburban areas, the fragility of structures exposed to tornado wind loads was similar (within 5%) to those exposed to hurricane winds. In open exposures, however, tornado load amplification relative to hurricane wind loads was approximately 1.37 to 1.55, indicating that the loads applied to buildings are 37-55% greater for tornadoes than for hurricanes at equivalent wind speeds.

b. Ongoing Research

NSSL has a research effort underway, led by CIMMS Post-Doc Melissa Wagner, to document wind damage in the Southeast U.S. during the PERiLS campaign (see below). This work will use multispectral imagery obtained using UAS to document wind damage to vegetation, and will attempt to qualitatively assess the relative contributions of straight, divergent, and swirling flow.

Stephen Strader (Villanova University) and David Roueche (Auburn) are also continuously documenting manufactured housing performance and failures as it relates to tornado events throughout the Southeast. The collection of this dataset is vital for determining long-term performance of manufactured home structures as it relates to tornado intensity, geographic location, and fatality rates.

2.6 Landfalling Tropical Cyclone Tornadoes

The Congressional appropriations in fiscal years 2018 and 2019 contained language indicating a special interest in mitigating the threat of tornadoes in landfalling tropical cyclones (LTC). In response, VORTEX-SE included this topic in its annual grant competitions.

a. Findings

Prior to VORTEX-SE, a review of the meteorological and forecasting aspects of Landfalling Tropical Cyclone tornadoes was written by Edwards (2012). This study nicely encapsulated much valid understanding of this phenomenon. LTC tornadoes were known to be most common in a sector of the LTC that included the right-forward quadrant with respect to motion. These tornadoes seem to have the characteristics of other supercell tornadoes, and (like is often the case in the Southeast) occur in relatively low CAPE and very large low-level shear. The diurnal CAPE cycle is found to be most pronounced further away from the LTC core, owing to greater amounts of cloudiness toward the core. Nocturnal LTC tornadoes are common, and sometimes strong, as is the case with non-LTC tornadoes in the Southeast. As of the 2012 review, there was a growing recognition of the forecast "ingredients" important for these tornadoes. There was also a recognition that these tornadoes are sometimes difficult to warn for because their parent storms are akin to "mini-supercells" and hence radar detection must rely on smaller, more poorly-resolved signatures. Finally, it should be noted that LTC tornadoes appear to be generally weaker than non-LTC tornadoes, but violent tornadoes can (rarely) happen.

Between 2012 and the present, significant improvements in convection-allowing forecast models, and the development of diagnostics such as Updraft Helicity, have allowed for much better delineation of tornado threat in LTCs. In one study supported by the NSF, Carroll-Smith et al. (2019) found good agreement between observations of tornado occurrence and WRF model forecasts of Hurricane Ivan (2004). Related work is ongoing with VORTEX-SE support in the Trier et al. project (see below).

As of this assessment, several VORTEX-SE research projects have been completed on this topic. However, there have been no reported findings in the formal literature.

b. Ongoing Research

VORTEX-SE has several studies underway in response to the Congressional appropriation language in the Department of Commerce spending bills.

One project is using North American Reanalysis Data to look at the environments of over 1200 tornadoes in over 100 storms, categorized by the type of scenario. This project is *Environmental and Storm-Scale Characteristics of Tornado-Producing Rainbands within Landfalling Tropical Cyclones* (S. Trier at al., 2019 grant). It appears on track to provide useful guidance to forecasters to anticipate tornado production in LTCs based on overall LTC characteristics, as well as the forecast parameters involving CAPE, shear, etc. Dereka Carroll-Smith and Roger Edwards are collaborators on this project, so in a sense it is continuing the earlier work cited above.

One of these projects involves the numerical prediction of tornado potential in LTCs. *Short-term Ensemble Prediction of Tornadoes in Landfalling Tropical Cyclones* (T. Jones et al., 2019 grant) is using the NSSL Warn-on-Forecast System (WoFS) to predict the spatial and temporal patterns of various threats in LTCs, including wind, tornadoes, and heavy rainfall. This system is being tested on events in realtime in 2020, with guidance available to operational forecasters for initial assessment.

Another research project (*Multi-disciplinary investigation of concurrent tornado and flash flood threats in landfalling tropical cyclones*, R. Schumacher et al., 2018 grant) is investigating the concurrent risk issues from both a meteorological and social/behavioral perspective. Initial findings seem to be pointing toward a re-emphasis of the earlier multi-hazard meteorological work that found an association between extreme rain production and storm rotation in historical data sets.

2.7 Forecast Model and Analysis System Improvements

a. Findings

Early in VORTEX-SE it became apparent that operational and experimental CAM guidance was often difficult to use when trying to assess tornado potential on the several-hour time scale. Thus, we supported efforts to understand the overall deficiencies in these CAM models. Schwartz et al. (2019) concluded that WRF ensembles generally produced more accurate precipitation forecasts (at 0-36-h lead times) over the central and eastern U.S. using 1-km than 3-km grid spacing. Some of the improvement arose from better representation of MCSs, which move more quickly (in better agreement with observations) in the 1-km forecasts owing to stronger cold pools.

John Lawson and collaborators have recently completed a project comparing 3-km vs. 1-km forecasts of four LCHS severe weather events during 2016-17. The model configurations were identical apart from the differing grid spacings and were both initialized from the 3-km NSSL WoFS (formerly NEWS-e). Overall, the 1-km forecasts performed better for a range of verification metrics, especially for strongly rotating storms.

b. Ongoing Research

Two projects are nearing completion at the time of this assessment. Ming Xue and collaborators began work in 2017 on *Evaluation and Optimization of Two New Scale-Aware PBL Schemes within WRF for the Prediction of Day- and Night-Time Storm Environment and Tornadic Storms during VORTEX-SE*. The project has resulted in the two findings described above. Ongoing work involves developing a WRF ensemble simulation of the 13 April 2018 case in which supercells produced tornadoes near Monroe, LA. The ensemble can be used to evaluate the tuned scale-aware PBL scheme, with special comparisons made with the downward-looking Compact Raman Lidar (CRL) that was aboard the NOAA P-3 aircraft for this event. This work appears to have morphed into a new three-year study being supported by the NSF.

The second nearly-complete project, *Understanding PBL Evolution and Surface-Driven Circulations with Simulations and VORTEX-SE Observations*, was begun in 2017 by Romine and collaborators. Of interest to CAM research, they have conducted a 50-member WREF ensemble simulation of the 5 April 2017 VORTEX-SE event. Perhaps unsurprisingly, the ensemble exhibited large sensitivity in afternoon convection initiation owing to an antecedent MCS.

Tom Galarneau and collaborators are investigating the accuracy and error sources of forecasts of HSLC events. Detailed analysis of HRRR forecasts of the 30 April 2017 QLCS tornado outbreak revealed that while forecasts with lead times up to 12 hours did well in placement of the QLCS, they emphasized a straight-line wind hazard rather than a significant tornado threat. The inability of CAMs to produce a pre-squall mesolow and attendant near-surface wind accelerations contributed to reduced vertical wind shear and storm-relative helicity in the pre-storm environment, representing a key factor that resulted in a more linear storm mode. Analysis of additional identified cases will reveal the generality of the results from the 30 April 2017 case and allow for further testing of the hypothesis that reduced latent heating within and subsidence warming ahead of the QLCS are key contributors to errors in the structure and intensity of the pre-squall mesolow.

VORTEX-SE has supported several NSSL projects related to the Warn-on-Forecast System (WoFS). These projects are preliminary steps toward evaluating and improving the performance of WoFS in the Southeast, eventually leading to CAM guidance that can significantly improve situational awareness in the 20 min to 2 hour lead time window. Jordan Laser and collaborators have compared mobile sounding and Lidar observations of the vertical wind profile within the inflow of 3 tornadic supercells in May of 2019 (5/17, 5/20, and 5/23) during the TORUS project to profiles predicted by WoFS at a similar storm-relative location. It was found that in each case WoFS underpredicted the strength of the low-level wind field and associated storm-relative helicity throughout the PBL, especially in the near field (<40 km) storm environment. In two of the three cases the entire envelope of WoFS member solutions predicted SRH values lower than those observed by mobile soundings and Lidar. Errors in profiles predicted by WoFS are smaller in the far field (40 - 80 km) storm environment, which suggests that WoFS is not fully resolving the storm's modification of the near field environment. Furthermore, though WoFS does show increasing low-level shear with the approach of the storm, the evolution of the wind field is different than observed by continuous Lidar observations. In two of three cases, Lidar observations show a backing and intensification of the near surface (<500 m) winds that is not reflected in WoFS predictions that show most modification in the intensification of southerly winds in the lowest 1 km. This result appears to be consistent with Flournoy et al. (2020), who also found that CM1-simulated supercells did not induce as much low-level backing as observed in TORUS soundings. *While none of these cases took place within the HSLC parameter space targeted by VORTEX-SE, there is no strong reason to expect the results do not substantially carry over to other regimes*. The results therefore suggest that *even state-of-the-art CAM ensembles do not satisfactorily represent the response of the low-level wind field to supercells in the Southeast*. This hypothesis could be tested using the same methods as the aforementioned studies but in the Southeast. Similar analysis should be conducted for other tornadic storm modes. One challenge that must be addressed by such studies is our incomplete understanding of how the near-storm wind field evolves in real storms, both supercells and other modes. For example, as Flournoy et al. (2020) pointed out, Wade et al. (2018) did not find evidence of near-field low-level backing in their comparison of near- vs. far-field tornadic supercell soundings from MPEX/V2 (though 0-1-km SRH was enhanced as expected).

In a related project relevant to, but not directly supported by VORTEX-SE, William Miller and collaborators are comparing WoFS forecasts run during the 2020 HWT Spring Forecasting Experiment that differed only in horizontal grid spacing: 3 km vs. 1.5 km. Both sets of forecasts were initialized from the same 3-km WoFS analyses. Several of the SFE cases occurred over the SE and/or were HSLC events, and similar comparisons are also being performed for the 2-3 Mar 2020 Nashville tornado event. These results will build upon the recent Lawson et al. results in illuminating the benefits of higher model resolution for LCHS events, which are typified by smaller storms.

3. Social, Behavioral, and Economic Sciences Findings and Ongoing Research

Given VORTEX-SE's overarching goal to reduce negative impacts (damage, injuries, loss of life, etc.) and to support protective decision-making, the program has included social, behavioral, and economic (SBE) science research since its inception. In the first few years of the program, SBE research focused on three broad, overlapping themes: how different physical and societal factors contribute to vulnerability to tornadoes in the southeast US; risk communication, risk perception, and the use of information in protective decision making; and understanding and improving how operational forecasters and NWS partners (such as emergency managers and the media) communicate about tornado risks with the public and how these groups work together in the tornado warning and response system.

The broad framing of these research themes was intentional. It allowed for multiple, varied research approaches in order that the research agenda of the entire project might be strengthened and made more robust through the inclusion of the diverse disciplinary, theoretical, and methodological perspectives that can be brought to bear on the Southeast tornado problem. The wide research net furthermore offered flexibility for new evidence-based knowledge to emerge and guide future research directions. Notably, VORTEX-SE is the first NOAA program to emphasize the needs of people living in a specific region related to tornado hazards, and as such, the research trajections have necessarily evolved as the program has evolved to address this novel question. Because tornadoes are dangerous natural, physical phenomena, and in recognition of the interdisciplinary nature of the VORTEX-SE goal, coordination and collaborations among the SBE scientists, the physical scientists, and operational forecasters has been and continues to be strongly encouraged.

Below, summaries are provided from past and ongoing SBE projects for VORTEX-SE (projects funded from the FY2020 opportunity are not included). Guided by the a priori research themes noted above and themes that emerged from research conducted, summaries are organized into subsections on Vulnerabilities (3.1), Risk and Hazard Information (3.2), Risk assessment and Decision-Making (3.3), and Forecasters and Forecast/Warning System Partners (3.4), Overlapping, Cascading, and Compounding Hazards and Risk (3.5), and a Meta-Ethnography of Tornado Epidemiology (3.6). *We parse the subsections in this way for exposition purposes, but there is overlap among them and in the results and needs covered within them.* Within each sub-section, we synthesize findings from research that has either been published (or is under review or in press) or that has been presented in a publicly available format (e.g., AMS conference). *We do not summarize results of ongoing research that has not been disseminated in an accessible matter. The list of ongoing research projects is available via the VORTEX-SE Community Forum.*

3.1 Vulnerabilities

Vulnerability has multiple definitions within the social and behavioral sciences (Singh 2014; Wisner 2016), including those that emerge from studies on population demographics, exposure and sensitivity to hazards, historical and root causes, as well as capacity to survive and rebuild after disaster (see Cutter et al 2009; Adger 2006; Blakie et al 2014; Faas 2016). Vulnerability to hazards arise through a confluence of economic, political, historical, and cultural forces that produce inequities in access to the resources needed to cope with the hazard. This can amplify risk of mortality and injury for those with the highest rates of vulnerability. The identification of vulnerability has been part of disaster discourse for many years (e.g., Burton et al. 1993; O'Keefe et al. 1976, Phillips et al. 2004, Wisner et al 2004). However, there has been significantly less empirical research on vulnerabilities in the context of tornado threats.

From the inception of VORTEX-SE, there was an explicit concern with understanding why the confluence of tornadoes and the peculiar vulnerabilities that exist in the Southeast have historically resulted in catastrophic loss of life and property. Past VORTEX-SE calls for research on this theme emphasized three subareas: 1) investigating how physical, social, and economic factors interact to contribute to harm from tornadoes in the SE, and which intersections of factors are the most important contributors in different local and household circumstances; 2) understanding different populations' capacities and current practices that can be utilized and leveraged to alleviate vulnerabilities and reduce harm from tornadoes in the SE; and 3) understanding the factors and decisions that enhance individual survival of tornadoes under different circumstances. Building improved understanding in area #1 was, and continues to be, deemed especially critical to help clarify the "Southeast tornado problem" and which types of events, circumstances, populations, etc. are most important to focus on in subsequent years across the program.

a. Housing Type

Mobile and manufactured homes have the highest fatality rate of any housing structure, with estimates of fatality rates of 15 to 30 times that of houses with roofs and walls tied to the foundations. This has been known since the early to mid 1970s, with data being officially recorded since the early 1980s. Despite this knowledge there is still a higher level of vulnerability to those living in mobile homes.

Liu et al. (2019) conducted research on how mobile home residents understand and respond to tornado warnings through multiple online surveys with a total of ~N=1000 mobile home residents and ~N=3050 general, fixed home residents across the Southeast. Key results reveal that mobile home residents have a lower sense of self efficacy to take shelter and perceive a lower false alarm rate as compared to fixed home residents. Mobile home residents turn to social media less and their local TV meteorologist more for tornado warnings compared to fixed home residents. A series of questions about tornado knowledge revealed that mobile home residents have slightly higher tornado knowledge rates compared to fixed home residents, although more than half of the members in both groups hold erroneous beliefs that the northeast corner of the basement is safest during a tornado or that you should shelter under a bridge during a tornado if caught out driving.

Strader et al. 2016 used historical tornado events, a finescale spatial resolution housing dataset comprising permanent and manufactured/mobile homes, and Monte Carlo simulation tool (e.g., Tornado Impact Monte Carlo Model (TorMC) and found that expected tornado-housing impacts in Alabama (i.e., the Southeast) are 88% greater compared to Kansas (i.e., the Central Plains) and that tornado-manufactured housing impacts are 385% higher in Alabama. Strader et al. showed that these statistics are driven by two fundamental built-environment characteristics: (1) the greater total number of manufactured homes *and* (2) the more sprawling (i.e., exurban and rural) land use density of manufactured homes. Together, these two factors create the elevated potential or probability for high-fatality tornado events and disaster in the southeastern U.S.

Other work by the Strader research group has focused on tornado-manufactured home evacuation vulnerability. Strader et al. (2019) utilized the geospatial dataset created in Strader and Ashley (2018) -- which contains over 200,000 manufactured home locations across Alabama -- to examine distance and time from every manufactured home in Alabama to the closest community designated tornado shelter (CDTS). Their analysis revealed that, because more than 75% of manufactured homes throughout Alabama reside in rural and exurban areas, the distance and time it takes for manufactured home residents to reach the closest shelter is nearly *double* that of those living in permanent homes. More specifically, compared to permanent home residents, it takes mobile-manufactured housing residents 5-10 minutes longer to reach their CDTS. This additional travel time coupled with short tornado warning lead-times has tremendous practical significance by limiting the ability for these populations to reach safe shelters, thereby leading to them sheltering at their home. Furthermore, this finding illustrates a risk communication conundrum when NOAA's and FEMA's main recommendation for manufactured housing residents is that they evacuate their homes when tornado threats arise. It also points to the issue and challenges of using purpose-built community tornado shelters as a single solution to the Southeast tornado problem because many manufactured housing residents simply live too far away to safely reach the community shelter once the tornado warning has been issued.

Strader et al. (in press) illustrates that manufactured and mobile home ground anchoring is critical during Southeast fatal tornado events. For example, the 2019 Beauregard, AL, (Lee County) EF4 tornado event killed 23 individuals, 19 of whom resided in manufactured homes. In all of the individual structural failures, the ground anchoring was the first point of failure during the tornado. Analysis by Strader et al. (in press) of geographic patterns and housing density showed that over 50% of the homes in the Beauregard, AL, tornado path were exurban or rural manufactured or mobile home structures. Comparatively, only about 13% of Alabama's total housing stock is manufactured or mobile homes. In other words, the proportion of manufactured and mobile homes in Beauregard was significantly greater than elsewhere, and the Beauregard, AL, tornado event is an exemplar of the high-fatality tornado events involving manufactured and mobile housing in the Southeast.

Ash et al. 2020 surveyed N = 246 mobile and manufactured home residents (MHRs) in Alabama and Mississippi to understand how their access to resources, beliefs about their home safety, and affective risk perception, among other things, relates to their comfort sheltering in their home during a tornado and their intention to shelter in their home given a hypothetical warning situation. They found that approximately half of MHRs are comfortable sheltering in their home during a tornado. Moreover, respondents' unwillingness to evacuate to a sturdy shelter was partially due to their belief that their home is safe and wind resistant. Additional geospatial analysis found that this belief in home safety was more prevalent in northern and eastern portions of AL where there tend to be larger mobile and manufactured homes. Additional results revealed what the authors term a "perception and vulnerability paradox", wherein those who had greater access to emergency resources and thereby the means to evacuate to safer shelters were less likely to perceive the need to do so, but those who were motivated to evacuate were limited in their ability to do so due to fewer resources.

b. Disabilities

Another component that contributes to social vulnerability to hazards and disasters are disabilities, which include physical, sensory, and cognitive impairments (Davis et al. 2013). Davis et al. discuss that many factors contribute to increased vulnerability for people with disabilities, including lack of access and equal opportunity to employment, education, transportation, and health care. Specifically in the context of tornado threats, when a tornado threatens and approaches, sensory disabilities can contribute to a lack of information access.

Sherman-Morris et al., 2020 conducted 25 semi-structured interviews by phone with residents of Alabama, Louisiana, and Mississippi who are legally blind, with the goal of understanding how they receive and respond to tornado warnings and what barriers exist for them regarding tornado warning and response. Results revealed that a majority of interviewees relied on television, phone alerts, siren, radio, and other people to receive tornado warnings. Furthermore, a good verbal description or the lack of detailed verbal description were of the greatest importance in participants' ability to effectively use warning information and act on it. This included audio for television warning crawls, and the level of description provided during severe weather coverage. Ample geographic description was important in their ability to personalize the threat. Multiple barriers were mentioned by the interviewees including inability to examine the radar information, to read the warning text, and to see environmental cues including of the tornado itself. Lack of public sheltering options and not being safe in mobile homes also were mentioned as key barriers.

Senkbeil et al. 2020 (under review) conducted research focused on improving tornado warning communication for deaf and hard of hearing (HoH) audiences. Emerging results suggest the need for more accurate and timely captioning on TV weather broadcasts, better text alerts, and for an American Sign Language (ASL) interpreter on screen during broadcasts but, importantly, situated in a way that does not obscure any part of the meteorologist's screen or radar display. Protective action decision making during recent tornado warnings showed that a greater proportion of deaf and HoH residents experience indecision and continued information seeking compared to the hearing population. Results also revealed that NOAA weather radios are not readily accessible by the Deaf and HoH population.

c. Additional Research on Vulnerabilities

LaDue and Friedman have examined how NWS meteorologists and county-level Emergency Managers identify vulnerabilities across their regions. Beginning in 2017, they conducted interviews and interactive mapping exercises with 39 NWS meteorologists and 53 emergency managers in Alabama in order to collect their knowledge about vulnerable people, places, and things that might be at risk during severe weather events. The goal is to draw on these vulnerability points in order to test and develop a tool that will provide NWS meteorologists and their core partners with an operationally-useful, streamline, and integrated map of critical vulnerability concerns in order to improve their spatial-situational awareness during operations. We will discuss the details of this tool (the Brief Vulnerability Overview Tool (BVOT)) in greater detail below, but, here we will report on their results regarding their analysis of these data.

Friedman et al. (2020) compared the 572 vulnerability points that were collected in their research with the 2018 Center for Disease Control (CDC) Social Vulnerability Index (SVI) in order to assess how well the vulnerabilities identified by NWS meteorologists and county-level meteorologists compared with census-tract level assessments of vulnerabilities. In general, the results of these comparisons confirmed that, when taken together, NWS meteorologists and EM knowledge of vulnerabilities *did* parallel CDC SVI, census-derived expectations regarding the spatial extent of vulnerabilities. However, at the same time, their work also showed that knowledge of specific *types* of vulnerabilities were, at times, different across these two communities. For instance, when the two groups were compared with each other against the CDC SVI regarding socioeconomic vulnerabilities (Theme One) which would include data regarding poverty, unemployment, per capita income, percentage of population without a high school diploma, etc. Friedman et al. found that NWS meteorologists identified more vulnerability points in census tracts with higher socioeconomic vulnerabilities compared to EMs. These analysis suggest that, while understanding specific vulnerabilities is critical, it is equally important to understand whether there are gaps in the knowledge of local decision makers about the spatial extent of these vulnerabilities that might require added attention.

3.2 Risk and Hazard Information

How people assess and respond to tornado threats is shaped, at least to some degree, by the information they obtain about them. In turn, forecast and warning information, preparedness and response information, and other messages about tornado risks present opportunities for interventions that have potential to enhance public awareness and protection of severe weather risks. Past VORTEX-SE calls for research on this theme emphasized research on understanding the interpretations and uses of warnings and other information -- including the roles of actual and perceived false alarms and near misses, experience, structure type and sheltering options, cultural factors, and so on -- among different members of the public in different circumstances.

a. Information Access, Processing, Interpretation, and Use

Reyes Mason et al. 2018 conducted a phone survey of ~N=1800 Tennessee residents to understand differences in warning sources and warning receipt for hypothetical scenarios in which a tornado occurs at night versus during the day. Results reveal that 84% of participants who were asked about a daytime tornado warning self-reported that there was a high or very high chance they would find out about it, whereas only 48% of participants indicated as such when asked about a nighttime warning. Additional analysis revealed that respondents who perceived greater risk of a tornado in their county and perceived greater warning accuracy were significantly more likely to say they would find out about a tornado warning during the day. Comparatively, respondents' reported likelihood of finding out about a tornado at night is significantly greater if they perceive greater risk of a tornado in their county and have previously experienced a direct hit from a tornado, but it is significantly less if they believe that luck is an important factor in tornado survival.

Liu et al. (2019) conducted research on how mobile home residents understand and respond to tornado warnings through multiple online surveys with a total of ~N=1000 mobile home residents and ~N=3050 general, fixed home residents across the Southeast (as also discussed above in the Vulnerability section). Their results showed that fixed and mobile home residents generally obtained tornado information from the same suite of sources, most commonly local TV meteorologists, followed by national TV meteorologists and other media, friends, and NOAA, obtained via traditional media, TV crawlers, wireless emergency alerts, social media, texts from loved ones, and sirens. There was no day-night difference in receipt from NOAA weather radio.

Sutton and Fischer (under review) collected eye tracking (N=171) and qualitative think aloud data (N=20) at a large southern university in response to an emerging tornado scenario. Participants were exposed to a series of Tweets that include tornado graphics (Day-1 outlook, watch, warning, and emergency) and Tweet message copy, drawing from existing messages that had been designed and disseminated by our WFO partners in Louisville, Kentucky. Eye tracking data showed fixation duration varied by message type; however, the longest allocation of attention was consistently placed on the message copy, the map, and the legend/risk information. Qualitative think alouds revealed that attention is drawn to visual features that provide distinction, such as the use of ALL CAPS in the message and the color red in the map. Colors that are unfamiliar, such as purple for the emergency, were found to attract visual attention but do not signal a heightened risk. Additionally, the use of multiple, but unrelated color schemes on a single image results in reduced comprehension of risk levels.

b. Probabilistic Tornado Forecast Information

Research on interpretations and uses of probabilistic tornado forecast information has potential to aid some vulnerable populations who need additional time to make informed decisions and find safe shelter (e.g., Strader et al. 2019, Ash et al. 2020).

Joslyn et al. (2020) and Demuth et al. (2020) conducted a web-based experiment with ~N=220 participants from across the U.S. followed by N=36 in-person semi-structured interviews with Alabama residents to evaluate how they perceive and respond to different visual representations of probabilistic tornado warnings. The visuals tested included color-coded probabilistic polygons (red-color and multi-color), numeric probabilistic (represented spatially and textually), and the traditional deterministic warning polygon. Key results from the experiment and interviews revealed that respondents infer a distribution of tornado likelihood ranging from ~50-80% chance of occurrence, when not explicitly given probabilities, i.e., in the deterministic polygon condition. When explicitly provided probabilities of tornado occurrence, their perceived likelihood most closely corresponds to the shown probabilities when the information is provided numerically without colors; when probabilities are coupled with colors (multi-color or red-color gradations), participants' perceived likelihood of tornado occurrence is systematically greater than the probabilities shown. Additionally, the experimental results revealed that many people interpret the tornado probability information as conveying severity. However, the interviews revealed that people reasoned in complex ways when assessing severity potential, including considering what parts of the natural and built environment could be affected and their structural integrity, and considering others' preparedness. The experimental results also revealed that people are less inclined to take shelter when explicitly told the tornado probability is 10%; however, the interviews revealed that people are not ignoring the warning information, rather they are engaging in other preparatory responses including preparing to take shelter and information seeking and sharing.

3.3 Risk Assessment and Decision-Making

When tornadoes threaten, people must assess their risk of being affected and what the response options are, and they must make informational and protective response decisions. A multitude of factors influence these processes, including their vulnerabilities (Section 3.1) and the risk and hazard information they receive (Section 3.2). Among additional influential factors are people's values, attitudes, beliefs, and worldviews; past experiences; capacities and barriers; and more. Accordingly, past VORTEX-SE calls for research on this theme emphasized research on investigating intersections among information, vulnerabilities and capacities, and protective decision making.

a. Risk Perception

Ellis et al. (2018) conducted a phone survey of ~N=1800 Tennessee residents to understand their perception of climatological tornado risk in their county. Results revealed that when county tornado risk is calculated as mean annual tornado frequency using SPC data (from 1965-2014), 54% of respondents underestimated the county risk. The percentage of participants underestimating their climatological risk increased to 81% when using model estimates of tornado frequencies that account for likely missed tornadoes. Additional analysis revealed that participants who had experience with a tornado hitting their home, hitting a building while they were inside, and/or hitting near where they live were 70% more likely (odds ratio of 1.7) correctly estimate or overestimate (rather than underestimate) tornado frequency of occurrence.

Ellis et al. (2019) utilized data from the same phone survey noted above of ~N=1800 Tennessee residents in order to assess how participants in three regions of the state perceive their local tornado characteristics (e.g., seasonality, diurnal timing) and their beliefs in protection from land surface features (e.g., hills, water bodies). Results revealed that, generally, participants correctly recognized the spring tornado season as when tornadoes are most likely to occur in Tennessee, but they did not recognize the heightened seasonal tornado activity in late fall and early winter. About half of the tornadoes in all of the Tennessee regions are nocturnal; most respondents correctly recognized this, but about 10% of respondents incorrectly indicated that 0 to 10% of tornadoes occur at night. Residents in hilly East Tennessee are more likely to believe they are protected by hills, whereas residents in West Tennessee are more likely to believe they are protected by water bodies, perhaps because of proximity to the Mississippi River.

Liu et al. (2019) conducted research on how mobile home residents understand and respond to tornado warnings through multiple online surveys with a total of ~N=1000 mobile home residents and ~N=3050 general, fixed home residents across the Southeast (as also discussed above in the Vulnerability and Risk and Hazard Information sections). They used three items to measure respondents' risk perceptions as how great of a risk tornado pose (a) to the survey respondent, (b) to the U.S. as a whole, and (c) to the southeastern U.S. The results revealed no difference between mobile and fixed home residents in how they perceived risk.

Broomell et al. (2020) surveyed N=2100 members of the public in the Southeast and Great Plains along with N=33 experts about tornadoes in the Southeast in order to elicit and compare public and expert judgments about tornado likelihood for different seasons, times of day, and storm system types. Results showed that public judgments deviated from the experts in systematic ways, revealing potential information gaps among the public. More specifically, relative to the expert sample, members of the public in the Southeast overestimated the likelihood of tornadoes in summer, underestimated the likelihood of tornadoes in winter, and underestimated the likelihood of tornadoes at night. Another contribution of this study is that it is the first to systematically capture the perceptions of a sample of tornado experts with knowledge about the SE.

b. Risk Assessment and Responses

Walters et al. (2019) utilized data from a phone survey of ~N=1800 Tennessee residents (the same survey as used by Ellis et al. 2018 and 2019, reported above) in order to identify public subpopulations based on their pattern of intended behaviors to a daytime or nighttime tornado warning scenario. The authors conducted a latent class analysis (LCA) based on participants' indications about whether or not they would take each of the following six actions in response to the hypothetical warning: do nothing, turn on TV or radio to find more information, search the internet to find more information, use app on a smartphone or tablet to find more information, look or go outside to check the weather, and contact friends or family. Results revealed that three latent groups of people emerged from the daytime warning scenario. The authors designated the three groups as (1) “tech users”, who were more likely to use the Internet and a smartphone app to learn about the warning, (2) “typical actors”, who were more likely to turn on the TV or radio, and (3) “passive reactors”, who were most likely to say they would do nothing but who also would engage in some responses, including turning on the TV and looking outside. Three groups also emerged from the nighttime warning scenario: (1) “tech users”, (2) “typical actors”, and (3) “non-reactors”, who were more likely to say they would do nothing and who were unlikely to engage in any other responses to get warning information. Additional analysis revealed for the daytime scenario that “tech users” and “typical actors” were more likely than “passive reactors” to take shelter. Similarly for the nighttime scenario, “tech users” and “typical actors” were more likely than “non-reactors” to take shelter. Further analysis of group members characteristics revealed, for the daytime scenario, that “passive reactors” are more likely than “typical actors” to perceive that tornado warnings are extremely or somewhat inaccurate, and are less likely to have direct experience of being hit by a nearby tornado. For the nighttime scenario, “tech users” were more likely than “typical actors” to have direct experience being hit by a nearby tornado and to have incorrect knowledge of what a tornado warning means. “Typical actors” were more likely than “non-reactors” to believe that bodies of water are protective from tornadoes.

Walters et al. (2020) conducted semi-structured interviews by phone with N=45 residents of Tennessee who, based on their responses to a survey (Walters et al. 2019), were characterized as having low access, low knowledge, or an unsafe response to tornado warnings. The interview goals were to understand reasons underlying these limitations and these people’s perceptions of NWS communications. Complementing the public interviews, the authors also conducted N=11 interviews in person with NWS forecasters in Tennessee to understand their perceptions of the public’s responses to tornadoes. Results revealed that most people reported an intent to seek additional information when they receive a tornado warning, and many turn to television because they perceive it as giving more detailed information than other sources. Public participants reported several barriers to receiving warnings, including loss of power when storms hit, poor cell or Internet service due to residing in a rural location, lack of storm radios, heavy sleep, and hearing impairments. Most participants knew about NWS guidelines for safe shelter-seeking, but mobile home residents indicated they would likely shelter in a hallway or bathroom rather than leave. Relatedly, the NWS meteorologists indicated that public shelters in Tennessee are rare, and thus they recommend people shelter with family, friends, or neighbors. Many public participants were satisfied with the NWS and its warning system, and they indicated that false alarms do not affect their responses to warnings. Nevertheless, some NWS personnel question the public’s trust in them, and they maintain beliefs otherwise about the effect of false alarms.

Demuth et al. (2019) conducted N=23 in-person interviews with members of the public a few weeks after the 22 January 2017 event in which a nocturnal EF-3 tornado killed 11 people in Adel, GA, and second EF-3 occurred about 12 hours later and killed 5 people in Albany, GA. Interviews were conducted with residents of both mobile / manufactured homes and fixed homes proximate to where the fatalities occurred. The interview goals were to understand how people get information, assess their risk, and respond dynamically to an evolving tornado threat, and how vulnerabilities interact with these processes? Results reveal that people are active risk managers, meaning they are actively seeking and receiving, attending to, and responding to forecast information. Moreover, the frequency with which they’re engaging in this process increases markedly as the tornado threat unfolds. Results also reveal that people often are being as safe as they can be. However, many people explicitly report that they have no safe place to go to protect themselves because there are no public storm shelters near them.

Smith et al. (2020) presented analysis of Twitter narratives of members of the public that were collected leading up to and following two deadly EF-3 tornadoes that occurred in southern Georgia on 22 January 2017, including a nocturnal tornado in Adel and an afternoon tornado in Albany. Fifty-five Twitterers who were in the Adel and Albany areas were identified, and their full Twitter narratives from 15 January 2017 through 29 January 2017 were collected, yielding over 20,000 tweets. The tweets were quantitatively content analyzed to identify mentions of different types of weather risk information, including (a) weather forecasts, watches, and warnings; (b) recommended protective actions, and (c) environmental cues. Sources of the weather forecast information also were coded. Key results revealed that people most commonly got their forecast information from a weather media source. Moreover, people are particularly attuned to tornado warning information; however, several people also mention SPC outlooks, which they typically learn about from a weather media source, most commonly a local broadcast meteorologist. In addition, environmental cues are important types of risk information, including “in situ” cues as well as “remotely sensed” cues from radar that people access using phone apps.

A project led by Friedman, Myers, and LaDue is aiming to generate empirically-grounded, observationally-based profiles of real-world, real-time, in situ-gathered human behavior at the household-level among the public in the southeast U.S. These data will be summarized into a number of “profiles” that will serve to ground future research on human behavior associated with severe weather events. In addition, these data will be provided to NWS forecasters, emergency managers, and other partners in the weather enterprise in order to serve as a foundation for reconsidering how they imagine the public’s preparedness for, understanding of, and response to severe weather communication and the need to take action. Although this project is in progress, results of the research design process and a summary of methodologies used for this in situ work have been presented by Friedman et al (2020).

Leslie et al. (2020) conducted quick response semi-structured interviews with survivors from the deadly EF-4 tornado that hit Lee County, Alabama, on 3 March 2019 in order to explore how different modes of communication influenced people’s sheltering decisions. They found that 85% of interviewees took their only or final sheltering action after receiving sensory inputs about the tornado, i.e., hearing, seeing, or feeling it. They further found that 100% of interviewees who had children in the room took some kind of sheltering action, whereas 69% of those without children did so. These results are part of an ongoing project that links survivor stories to forensic engineering with aims to reduce structural vulnerability and increase occupant survivability.

3.4 Forecasters and Forecast/Warning System Partners

Fully realizing the goal of VORTEX-SE to reduce harm and loss of lives requires also studying and working with the originators and mediators of forecast, preparedness, and response information. How these groups conceptualize, assess, and communicate tornado risks in the Southeast is complex and multifaceted. Past VORTEX-SE calls for research on this theme emphasized research on (a) investigating forecasters’ interpretations and use of different types of information in decisions about whether, when, and how to issue warnings and other products; and (b) understanding how uncertainty affects the forecast and warning process (for forecasters and partners) and information gaps that contribute to uncertainty.

Ellis et al. (2020) used a mixed-method approach, including interviews with 11 NWS forecasters in Tennessee, to assess how convective mode—discrete supercell, cell in cluster, cell in line, or quasi-linear convective system (QLCS)—affects the NWS procedures. Results revealed that forecasters identified challenges in detecting tornadoes in convective modes other than discrete supercells, including short-lived QLCS tornadoes. Key forecaster concerns other than convective mode included storm speed, outbreaks, and lack of ground truthing at night. Forecasters differed in their motivation to either warn on every tornado or avoid false alarms.

Liu et al. (2020) conducted an ethnography at three NWS forecast offices during tornado threats and events in order to investigate what message strategies forecasters employ to communicate tornado risks. They observed forecaster operations, conducted N=32 interviews with forecasters, and analyzed 151 social media posts issued by the three offices. Results showed that forecasters update social media posts with language indicating if they expired in order to mitigate the risk of people viewing outdated information. Forecasters extensively use visuals to convey tornado risk on social media; they use photos, GIS data, radar loops, and radar scans to help members of the public see what is happening during a severe weather event and motivate protective action. Moreover, forecasters aim to motivate action through careful word choices; by updating tornado event timing; by providing specific precautions publics should take; and by employing their personal social media channels to communicate about risks. Forecasters also aim to avoid using fear appeals in how they communicate tornado risks because they are concerned that such “fear mongering” can damage their reputation as an authoritative source for severe weather information and thereby be ineffective.

Between 2016 and 2017, LaDue et al. (Friedman 2017; Friedman and Wagner 2017) observed 17 forecasters and 32 core partners (emergency managers, deputies, fire captains, public works officials, etc.) during 14 severe weather events (7 in 2016, 7 in 2017) in northern Alabama. Drawing on these observations and 257 recorded interviews (178 NWS WFO and 79 core partner) they investigated how uncertainties affected NWS WFO forecasting and communication with core partners and publics during convective events. In addition, they observed how those forecasting uncertainties cascaded down to emergency manager decision-making before, during, and after these events. Results showed that NWS meteorologists in the study region faced heightened forecasting challenges due to poor numerical model guidance, higher prevalence of high shear-low CAPE events, and the problems associated with a climatology that produced year round tornado potential. These challenges created uncertainties among NWS WFO meteorologists that impacted the timing and confidence with which they communicated forecast information to core partners/EMs. LaDue and Cross (2018) and LaDue (2019) found that NWS WFO’s reluctance to overstate the certainty of an uncertain forecast left core partners/EMs to try to find their own forecast and weather information, or left them having to make personal appeals to the WFO for the WFO’s “best guess” regarding the timing, mode, and severity of convective events Results also showed the level of frustration among core partners/EMs as they faced their own set of operational uncertainties while simultaneously feeling like they were not receiving the NWS WFO’s “best guess” forecasts. Friedman and LaDue (2019) found that NWS WFO meteorologists were more likely to communicate best to their partners when they were aware of the vulnerabilities that were of immediate concern to those core partners/EMs.

3.5 Overlapping, Cascading, and Compounding Tornado Hazards and Risks

Weather hazards do not always occur as single instances of a particular threat. Instead they can overlap in time and space, compounding risk and vulnerabilities for people. In other instances, hazards may damage or destroy homes, compromise the ability of individuals to work or maintain finances, or injure people thereby leaving them more exposed to future hazards. These compound and cascading impacts are difficult to capture given the emphasis on individual threats in the warning system and the way events are scoped to only include the time period before and during a hazard. Tornadoes that occur with flash floods, or TORFFS (Nielsen and Schumacher 2015) are one type of compound hazard common in the U.S., with over 400 TORFF warnings issued each year. When they occur as part of a mesoscale event, like a supercell or QLCS, warnings can offer conflicting safety advice in a relatively short period of time, leaving individuals confused about the action they should take. In a Landfalling Tropical Cyclone context, overlapping hazards multiply and dynamically change over the course of several days. Tornadoes can co-occur with flash floods, aerial flooding, and storm surge, and they can cause damage to homes and property before flooding, leaving people more exposed to harm, or they can occur as people are evacuating from flooding to the highest parts of their homes or on roofs. While some co-occurring events, like TORFFs, have been minimally studied, other compound hazards and the cascading impacts are yet to be studied.

a. Mesoscale Context

Henderson et al. 2020 conducted ethnographic observations and interviews at a NWS Forecast Office (FO) in the Southeast over the course of a mesoscale convective event that produced a TORFF. The authors examined several dimensions of forecast operations, including practices, policies, and procedures. Drawing on the theories of social amplification of risk (SARF) they identify four “sites” where amplification and attenuation of threat risk can intentionally and/or unintentionally occur: 1) in the beliefs forecasters have about dangers of respective threats and their publics’ beliefs; 2) in the coordination with national centers, like the SPC and WPC, in developing communications and timing of messaging for respective threats; 3) in the language/terminology used to describe threats, which at times can highlight one threat as a risk (i.e., tornado) and another as a phenomena (i.e., heavy rain); and 4) division of expertise in the office or division of space in warning operations can hinder communication in real time about TORFF threats. Additional insights emerged related to types of TORFF-like events that are not obvious. With overlapping flash flood warnings and severe thunderstorm warnings with “tor possible” tags, for example, contradictory advice can be generated about getting to a higher location for flooding and getting lower for tornadoes. Finally, the authors highlight that although many flash flood warnings may not include advice to “get to high ground,” which is problematic for those also seeking shelter from tornadoes, advice to “turn around, don’t drown” can unintentionally pose challenges for those in mobile homes or other unsafe structures who may need to drive to safety. Additional research should be done to understand TORFFs in different NWS FOs to build knowledge of common challenges and practices across different office cultures, practices, and types of flooding. Among the implications for NWS policy and practice discussed in the paper are that there may be need in some offices for more explicit, ongoing coordination between those in operations who issue severe convective warnings (i.e., tornado, severe thunderstorm with tor possible tags) and those who issue hydrology-related products (e.g.. flash flood or river flood warnings).

b. Landfalling Tropical Cyclone (LTC) Context

Bica et al. (under review) collected unique contextual streams for 209 accounts of people in the public who experienced Hurricane Florence and tweeted about both tornadoes and flash floods. Authors analyzed the full contextual streams of users from Sept. 8-20--the date range that comprises the two-week period surrounding Florence's landfall on 14 September--to understand how people talked about their experiences with tornadoes and flash floods, for a total of 23,937 tweets. Using the concept of liminality from anthropology to understand how people in highly constrained disaster contexts like overlapping hazards use social media, authors identified several processes at work. In combination with existing socio-economic and demographic vulnerabilities that are already limiting, they found that TORFF constraints shaped a range of possible actions taken in response to threats, including ability to evacuate, feelings of powerlessness with respect to authority, like employers; negotiating authorities that influence decisions counter to hazard advice; advocacy for those unable to advocate for themselves; and documenting or surrendering to the experience when unable to change one's circumstance. Inductive analysis led to interpretation of these posts as arising from the liminal experiences of disaster, or periods of transition when people are "betwixt and between" states of normality. In observing people's moment-to-moment experiences of uncertainty in situ as documented on social media, findings illustrated the felt experiences of liminality in disaster and how these are supported by a social media audience. The paper also considers these findings in relation to the experiences of the emerging 2020 COVID -19 pandemic.

Spinney et al 2020 analyzed both local newspaper articles and 369 tweets from 27 Twitter users about Hurricane Florence related to overlapping tornado and flash floods threats for the Durham County Public Schools. Findings revealed ethical debates about the responsibility over student safety and debates about transparency of policy decisions regarding school closures, including issues of problem definition of risk and organizational influence over public response. One primary finding is that members of the public rely on social structures like schools to be transparent about their decision making processes and policies related to severe weather and school closings and openings. Another is that TORFFs increase the challenges institutions face in making these decisions in the face of previous closures amid similar overlapping threats and the expectations parents understandably have for the safety of their children.

3.6 A Meta-ethnographic Analysis of Tornado Epidemiology

Sharpe (under review) conducted a meta-ethnographic analysis of tornado epidemiology in the U.S. The analysis coupled a review of "grey" literature from Centers for Disease Control and Prevention (CDC) reports, NOAA Service Assessments, and grant reports with peer-reviewed journal articles, all in order to confirm what is known about tornado epidemiology and to identify knowledge gaps. Multiple key themes emerged from the analysis. Some of these themes are well-known, such as vulnerability of mobile home residents. But the layers of complexity underpinning vulnerabilities were also investigated, linking to other so-called 'vectors of vulnerability', a conceptual framework that identifies levels of complexity that collectively undermine efforts to reduce tornado impacts on communities.

A key finding is that complexity exhibited by these vectors of vulnerability is key to understanding drivers of risk, and how these impact survivability. There is not one simple solution to reducing risk of fatality because there are multiple vulnerabilities, which when coupled with the tornado magnitude, all underpin varying degrees of risk that likely impact on survivability of tornadoes.

Analysis of literature highlighted the multiple vulnerabilities that drive increased risk of loss of life or injury. These do not exist in isolation but conspire together to weaken survivability outcomes. In order to understand these and frame them in a manner that acknowledges their complexity, a new terminology was needed. Consequently, a vector of vulnerability was defined as ‘a vulnerability resulting from a specific vector that improves or worsens the impact for individuals in the path of a tornado’. A tornadic vector of vulnerability is one that has the capacity to carry and spread increased vulnerability, with each vector having their own weight in terms of strengthening or weakening survivability of those in the path of a tornado. This weighting is likely to be reflected by the way each vector increases fatality rates or enhances survivability. There is also complexity within each vector of vulnerability as they are also impacted by access to finances, social networks and education and learning opportunities.

Although many different vectors of vulnerability were identified, certain vectors were seen as having the greatest impact on driving mortality. These included living in mobile homes, access to sheltering options and receiving warnings. Of these, mobile homes were identified as a vector of vulnerability with the highest potential weight, reflecting the physical vulnerabilities that they represent in impacting on fatalities.

In terms of human behaviour and decision-making, ascribing blame or assuming ignorance on the part of mobile home residents or complacency about their situation, was not borne out by the literature. Instead, the literature points out that many are aware of risk and take what they believe to be appropriate action, such as going to an interior bathroom or closet. However, the weaker structural integrity of mobile homes when coupled with poor anchorage and maintenance of tie down struts, combine vectors of vulnerability that enhance risk of fatality to residents of these structures.

In terms of risk, there are issues of how information is received, whether it is trusted and most importantly, whether citizens act not only in the way that we know enhances survivability, but the options that they have to act upon warned tornadoes. Certain vectors of vulnerability limit options and survivability (mobile homes, lack of shelter access, etc.), while known risks are often enhanced by the perception of the risk, which includes whether warnings are received or able to be received. This is especially pertinent for nocturnal tornadoes where individuals may be at home in weaker structures (MMHs) without access to sirens (especially in rural areas) and with mobile phones off or not able to receive information. Simple messaging about the need for NOAA weather radios may be of use for these populations.

Large loss of life in mobile homes and indeed in permanent homes is also linked to lack of access to shelters or sheltering options (for example taking shelter in a nearby permanent house that has a basement or internally protected space). This gap might be reduced or closed by allowing communities to map their own risk as well as their own capacities in terms of sheltering options that currently exist locally.

Currently, capacity is not a widely expressed method for underpinning tornado survivability. In order to understand and enhance capacity, there may be a need to augment our collective approach, moving away from top-down and expert-led approaches to bottom up and embedded ones, allowing for experts to contribute from across communities. Widening communities of practice may help to close value-action gaps between intentions and behaviour, building capacity instead.

A key part of identifying capacity is knowledge about the survivability of tornadoes. One of the principal guiding aims of undertaking tornado epidemiology research was to provide a baseline for survivability as well as acknowledging and understanding what drives fatalities. But baselines require a knowledge of exposure rates in tornado events so that there is an understanding of both fatality rates and survivability rates. This is an area of future research that is likely to reap significant benefits.

4. Program Recommendations

4.1 Physical Sciences Emphases

a. PERiLS

One key aspect of VORTEX-SE during the next few years will be the PERiLS field campaign. PERiLS has the potential to provide a variety of important new insights, including better understanding storm processes, storm/environment interactions, validation of mesoscale analysis systems and CAM guidance, and others. This section describes the PERiLS experiment.

1. Description

Over the past 10 years, ~ 1400 tornadoes occurred annually in the U.S., 20-25% spawned by quasi-linear convective systems (QLCSs) (e.g., Trapp et al. 2005, Smith et al. 2012, Ashley et al. 2019). This percentage is even higher in the Southeastern (SE) U.S. (Anderson-Frey et al. 2019), where the population is particularly vulnerable to tornado impacts (Ashley et al 2008; Strader and Ashley 2018). While a multitude of field campaigns have focused on collecting data to better understand supercell tornadogenesis (e.g., VORTEX, VORTEX-2, ANSWERS, ROTATE, RiVORs, TORUS), none have focused specifically on QLCS tornadogenesis. Our lack of physical understanding is compounded by the short temporal and small spatial scales characteristic of QLCS tornadogenesis, which often are not captured by the conventional operational radar network (e.g., Trapp et al. 1999; Davis and Parker 2014). Although we have some idea of the environments in which QLCS tornadoes occur, climatologies and case study simulations show that tornadoes tend to occur within a small fraction of the total area that appears favorable (e.g., Sherburn et al. 2016). Moreover, simulations suggest that the pre-QLCS environment evolves rapidly in response to vigorous large-scale forcing (King et al. 2017), but the magnitudes of these hourly (and even sub-hourly) changes have yet to be measured. These gaps in our knowledge critically reduce our ability to warn the public, because common forecast skill metrics (e.g., warning lead time and false alarm rate) are significantly worse in QLCS tornado events than in supercell tornado events (e.g., Brotzge et al. 2013).

Previous VORTEX-SE field campaigns have focused on various aspects of tornadogenesis in greater northern Alabama. During three spring VSE field campaigns (2016, 2017, 2018), QLCSs were the primary storm mode associated with tornadogenesis. These campaigns provided proof-of-concept that QLCSs (and their near environments) can be sampled with targetable ground-based instrumentation in a region not traditionally considered optimal for tornadogenesis studies (because terrain and forests hinder a traditional “storm chasing” approach). The large spatial scale and longevity of QLCSs are advantageous for deploying non-chasing instrumentation; a targeted network can be deployed to pre-scouted locations several hours in advance of an approaching QLCS, with a high likelihood of useful data collection.

PERiLS will focus on the following objectives:

Objective 1. Low-level Vortexgenesis: Identify the mechanisms for mesovortex formation.

Objective 2. Tornadic Mesovortices: Identify the characteristics and mechanisms that distinguish between tornadic and non-tornadic QLCS mesovortices.

Objective 3. QLCS Environment: Identify the environmental variability and storm-environment interactions that are associated with QLCS mesovortexgenesis and tornadogenesis.

Objective 4. Cold Front and Cold Pool Processes: Characterize the role of cold frontal processes vs. system-generated cold pools in the evolution of strongly-forced QLCSs.

Objective 5. Mixed Phase Drafts: Evaluate whether the kinematics, microphysics, and electrification of drafts with more active mixed phase processes are associated with rotating mesovortices.

2. Plan

The field phase of PERiLS is proposed from 1 March to 15 May 2021 and 1 March to 15 May 2022, most of "MAM" in the SE U.S. The following instrumentation is necessary to collect the observations needed to address our objectives and hypotheses. From NSF, we propose to deploy: 1) a high-transmit-power, 1-degree beamwidth, dual-pol, deployable C-band radar ("C-band on Wheels", "COW"), which will complete a three C-band multi-Doppler network to map 3D winds in QLCSs at high spatial and temporal resolution; 2) a high-transmit-power, fast-scanning, 1-degree, dual-pol X-band radar ("DOW7") to capture rapid evolution of features along QLCSs' leading edges and to complete the X-band dual-Doppler network; 3) surface weather stations ("Pods") and mobile mesonets to increase the density and targetability of surface observations both ahead of QLCSs and in their cold pools; and, 4) sounding expendables to launch frequently from multiple sites before, during, and after the QLCS to identify environmental signals of possible tornadogenesis not captured by the observational sounding network. ***NOAA is expected to provide a multitude of ground-based instruments as in-kind support:*** the most critical such instruments to this proposal are two mobile C-band radars ("SMART-Rs", "SR1" and "SR2"), a mobile X-band radar ("NOXP"), and an array of 24 surface weather stations ("StickNet"). In addition, an expected NOAA RFP will result in support of additional scientific instrumentation and scientific analyses. PERiLS NSF PIs will provide sounding systems, drones equipped with cameras, and a 915 MHz wind profiler. **PERiLS highly leverages synergy and collaboration between NSF- and NOAA- funded efforts.**

3. Expected New Knowledge

The aforementioned objectives and hypotheses can be addressed through various combinations of evolving 3D wind fields derived from multi-Doppler retrievals, surface measurements, and environmental profiles. The targeted observation network proposed for PERiLS will provide an unprecedented data set for advancing our understanding of QLCS processes and the environments that promote tornadogenesis in the southeast. Numerical modeling will draw from these observations and analyses to augment our understanding of the underpinnings and relative importance of various processes in QLCS mesovortex and tornadogenesis. The highest priority will be integrating observations into 4D multi-variable datasets to obtain the best possible understanding of these systems.

b. Recommendations for Physical Science Emphases and Needs

Because of the current nature of funding in VORTEX-SE, we must emphasize goals that are achievable in 1-2 year time windows. As a NOAA program, a clear vision of the path to societal benefit is needed for all of our activities. Specifically, we assess that much more emphasis needs to be given to obtaining new knowledge to improve forecasting in the 20-minute to 2-h time frame, with the intent of improving threat awareness in general, and allowing improved forecast reliability for people and groups that require longer lead times than typical tornado warnings.

Basic science, often requiring 5-10 year efforts, or more, are more appropriate for other funding approaches outside of VORTEX-SE. Therefore, VORTEX-SE physical science research should be focused on gaining understanding that will improve forecasts (currently outlooks, watches, warnings and related communications) and numerical guidance of tornadoes utilizing existing observing systems. Particular focus should be placed on improving understanding of the near-storm environment with an end-goal of capturing interaction between storm processes and the antecedent environment. The research should also include an emphasis on developing frameworks and conducting focused field research that can identify the most appropriate mix of observations to improve forecasts, both human and numeric, in the future.

In light of the research conducted thus far in VORTEX-SE, we assess that the following topics have a greater potential for near-term benefits that the program seeks to accomplish:

- Assess the validity of mesoscale features found in analysis systems such as 3DRTMA, and develop new knowledge concerning new parameters, strengths, weaknesses, and interpretations of these sorts of forecasts tools;
- Identify radar precursors to tornadoes, especially non-kinematic, in convection of relevance in the Southeast;
- Identify the mesoscale features in the storm inflow environment that are related to tornado potential, with the intended outcome being increased human forecaster awareness and ability to use appropriate data sources and analysis tools, as well as identification of deficiencies in Convection-Allowing Models;
- Increase our understanding, via climatological analysis, of the varieties of tornadic QLCS vortices in the Southeast and their associated damage intensity.
- Increase our understanding of storm processes associated with tornadoes, and how these processes are related to processes in the near storm environment, with an *essential emphasis* on developing prototype analysis tools that utilize conventional observations;
- In order to improve short-term forecast guidance, explore Machine Learning tools, with inputs possibly including 3DRTMA, MRMS, CAM output and similar data alone or in combination;
- Expand climatological examinations of the role of terrain roughness and land use/land cover in the Southeast US tornadogenesis threat;
- Whenever feasible perform careful damage analysis of SE US wind events, with an emphasis on qualitative characterization of swirling, divergent, and straight components.

Further, we assess that the following topics and approaches should perhaps be *de-emphasized* in VORTEX-SE, being more appropriate for other funding agencies and programs:

- Forecast model development and improvement (outside the VORTEX-SE scope);

- Precipitation physics studies outside of the context of operationally available data (outside the VORTEX-SE scope);
- General PBL studies not focused on near-storm environments (outside the VORTEX-SE scope);
- Seasonal prediction; effects of climate change (outside the VORTEX-SE scope);
- Instrument development and validation (lacking short term benefit);
- *Observational* studies that aim to understand the role of terrain and land use (defer until these increase in feasibility and clear operational benefit); and
- Tornadoes in landfalling tropical cyclones (current work should be completed and this topic revisited in future assessments).

It is important to understand that these topics may be vitally important science, but are just not deemed to *currently* fit within the VORTEX-SE paradigm of near-term societal benefit.

1. Needs: Terrain and Roughness Impacts on Storms and Tornadoes

VORTEX-SE research needs must be assessed from the perspective of application for societal benefit, as noted in the Introduction. It is our assessment that additional basic research is required to understand how terrain features modify the mesoscale environment, making it more conducive for tornado formation. Because this is basic research, locally applicable, and without a well-defined path to societal benefit, it is best suited for funding outside the VORTEX-SE program.

Because these terrain influences appear to be local, we assess that it is appropriate to now transfer the accumulated knowledge to the appropriate local Forecast Offices. It is possible that these offices can further refine the knowledge through careful monitoring and comparison of the environments depicted in mesoscale forecast models to actual outcomes. These refinements are expected to vary with large-scale environments and forcing, and low-level stability and wind profiles. We further assess that any additional VORTEX-SE supported work should be a relatively low priority.

We assess that there is some potential for improvement in situational awareness based on the work of Hua and Chavas, first by extending that approach to other areas of the Southeast, and then by using similar approaches to assessing the role of mesoscale land use variations. This should be explored in the operational context of increasing the understanding of where tornadoes are most likely to form given the existence of a storm exhibiting tornado potential. If there are no significant relationships that can be demonstrated between tornado formation, terrain roughness (outside of Arkansas), and land use, this line of research should be suspended in VORTEX-SE until new, testable hypotheses and promising approaches emerge.

2. Needs: Internal Storm Processes

It is likely that significant advances can be made in VORTEX-SE in the understanding of internal processes in tornadic storms. These advances should be expected from the planned PERiLS field campaigns (Sec. 4.1.1). For example, It is likely that identifying the relevant processes that lead to tornado formation will allow us to identify precursor signatures in remotely sensed data, including radar velocity, dual-polarization data, lightning mapping, and satellite data. These precursor signatures can be conveyed to operational meteorologists and (eventually) incorporated into radar algorithms or analysis systems such as MRMS. Much as initial work in severe storms focused on steady, equilibrium, and linearized storm-scale processes on the boundary between meso-gamma and -beta scales, this work should aim to specify the smaller internal time and space scales of such precursor signals so that it is clear what observational and modeling capability is required to utilize them in operations.

Understanding the internal processes and their precursor signatures has the potential of adding to useful lead time in identifying the tornado threat. It is possible that some of these signatures may emerge 20-30 minutes prior to tornado formation, with increasing utility as the event approaches. We believe this time frame can merge with even longer periods of useful threat awareness coming from knowledge of storm-environment interactions (sec. 2.1.3).

Because of the potential for advances that can be transferred to operations, we believe that VORTEX-SE should make every effort to ensure the best possible data collection in the PERiLS campaigns, as well as fully supporting subsequent analysis efforts. Consistent with previous severe storms field campaigns, we anticipate that the peak output of new knowledge will occur roughly five years after the last field campaign, with important findings being produced up to ten years after that date. If possible the NWS should be engaged in the field campaigns so that researchers can gain understanding regarding perceptions of operational issues. Research projects should have a clear conception of the path to operational benefit, with an emphasis on training and algorithm demonstration.

Because VORTEX-SE already has invested in a significant amount of data collection, existing cases should be documented in the VORTEX-SE Community Forum as a mechanism to advertise cases and data sets that can be exploited for additional new knowledge.

Ongoing work exploring microphysics, cold pools, and electrification should be monitored for additional progress. If promising results emerge, the program may be able to move the results toward improving operational model precipitation physics parameterizations, and toward lightning observations that are able to be used routinely to discern the dynamic processes and evolution of potentially tornadic storms.

3. Needs: Storm Environments, Storm-Environment Interactions, and the Planetary Boundary Layer

Although this topic is of fundamental importance to improving tornado forecasts and warnings, VORTEX-SE has made very little progress in it thus far. There are perhaps two reasons for this. First, it has proven very difficult to observe storm/environment interactions in the Southeast U.S. Initially our field campaigns were focused in the small subregion of the Tennessee Valley in northern Alabama, where the complexities of instrument deployments are large (albeit smaller than the Southeast in general). This experience has led us to the design of the PERiLS campaign (sec. 4.1.1) for which we have identified six sub-regions in which we can deploy instrumentation based on the road networks and land use.

The planned PERiLS field campaign (see sec 4.1.1) will be an important first step toward characterizing prestorm environments in the Southeast. Special emphasis should be incorporated into that project to ensure observation of the relevant time and space scales as they are currently understood. It is important that these observational data sets become available quickly, and that analysis efforts are supported through the typical multi-year analysis period that follows a field campaign. Special emphasis should be given to validating analysis systems such as 3D-RTMA (or similar).

Understanding storm/environment interactions, with many of the most important processes possibly occurring in the PBL, is one of the greatest unmet needs in VORTEX-SE physical science research. A basic characterization of those processes should begin to increase forecast skill in the 20 min to 2 hour time window. It will enable the evaluation of tools such as 3D-Real-Time Mesoscale Analysis (3D-RTMA) and the validity of processes and features depicted in CAM guidance. And it will possibly highlight the need for changes to observing systems to better capture these features and processes.

VORTEX-SE should encourage climatological studies of environmental forecast parameters, features, and evolution using existing data sets (operational and field campaign). A prime example would include ongoing work to use high-resolution VAD data to document hodograph evolution as a function of distance from tornadic and non-tornadic Southeast convection.

The route to operational benefit likely initially includes direct knowledge transfer via in-person training and interactions between researchers and operational meteorologists. VORTEX-SE should attempt to develop knowledge transfer in the context of the Community Forum as well. On longer time scales, benefit will accrue through improved operational analysis and numerical forecast systems.

It is possible that UAVs will become useful in the near future for routine lower atmosphere soundings. Meteomatics, for example, conducts operational UAV soundings in IFR conditions in Switzerland with observations assimilated by operational forecast models. Their ceiling is now 3 km. In the U.S., the progress has been slower because of a more difficult regulatory environment. VORTEX-SE should monitor the progress of the "operationalization" of UAV soundings as a potential system to augment or replace remote-sensing sounding approaches. If possible, frequent UAV soundings should be evaluated for operational utility, and possibly Data Assimilation, in PERiLS.

4. Needs: Climatology

At this time, there is still considerable uncertainty about the nature of the phenomena producing wind damage in the Southeast U.S. This is a result of a number of factors. Damage areas are often inaccessible owing to forestation. It is more difficult to attribute damage to swirling, divergent, and straight flow components owing to fast storm motion leading to the appearance of straight damage. And in general, Potvin et al. (2019) estimate that approximately half of tornadoes have gone unreported within the U.S. since 1975, with the deficiency increasing in less populated areas. Recent (unpublished) work by Potvin et al. suggests that even in the most recent decade, nearly half of all tornadoes were unreported, and more than half of all significant tornadoes were either unreported or underrated. Understanding damage in the context of radar signatures and forecast parameters should lead to improved forecasts and warnings. Thus we believe there should be significantly increased emphasis on obtaining detailed damage survey information, including from aerial platforms, in as many cases as possible.

VORTEX-SE should support work similar to that being done by Homeyer, Potvin, and collaborators. This work shows promise of discovering new radar indications of tornado potential, including basic morphological characterization (mesocyclone erectness) and microphysical characterization. Once these and similar findings are validated with sufficiently large samples, it is suggested that prototype algorithms be demonstrated in operational contexts (e.g., perhaps through a web application).

The wind and structural engineering (WSE) portion of the VORTEX-SE scientific steering committee sees itself as a bridge between the physical sciences and the social and behavioral sciences and believes joint participation in research projects is necessary to achieve the goals of VORTEX-SE. Therefore, the research needs will be organized in terms of the areas which could be of most benefit when considering the research needs of both groups.

From a physical science perspective it is clear that a scale mismatch exists between what atmospheric scientists and engineers are primarily interested in. WSE need to do a better job of communicating these needs and why they are important. For structural loading and response, WSE are mostly interested in spatial scales on building scale or less and time scales in the order of seconds or less. Experimental methods that can address the smaller scales would be a research need WSE could benefit from, including four-dimensional, high resolution in-situ measurements to quantify near-surface wind fields and associated turbulence (e.g., wind profiles, acceleration, vertical component of the wind), LES-CFD and wind tunnel studies. These links must be established because without them, the intensity estimates for tornadoes will remain highly uncertain at best, and likely erroneous when relating to design levels and other non-tornadic windstorm events. Research involving simulations should be directly linked with observed behavior in real tornado events through radar measurements, in-situ measurements or damage surveys (see next paragraph). The scale mismatch contributes to confusion on the wind speed – damage relationship and how this relationship is both communicated and operationalized. A broad example is relating “wind speed” to “damage”. There are other factors at play between a wind speed value and a damage level. Most notably terrain characteristics, building aerodynamics and structural response. A wind speed of 100 mph at 10 m height, 3-s gust and open terrain for example may cause a wide range of damage levels when accounting for one or all of these factors. A specific example is the attribution of mesovortices to individual building level damage. The scale of a mesovortex is much larger than a single building, and when examining building-level damage, the damage is likely caused by other factors described above. This sort of factor assessment is not explicitly included when estimating tornado intensity through the Enhanced Fujita Scale. With that being said, it is important to distinguish tornado-scale features and behaviors (e.g., corner flow region, sub-vortices) as they will be influenced by terrain and modify building aerodynamics. Some preliminary VORTEX-SE research is suggesting that obstacles such as terrain and buildings may feedback on the tornado itself and is an extension of the work of Satrio et al. (2020).

As for collection of point-based surface measurements, which to put mildly, present challenges in a near-tornado environment, detailed damage surveys are a clear research need for WSE in the context of VORTEX-SE. Damage surveys can provide insight on a number of processes important to both disciplines. For example, near-surface wind fields (e.g., Rhee and Lombardo, 2018) and processes can be assessed considering terrain and topography influences using tree-fall patterns. A number of other key parameters including tornado frequency, intensity and maintenance, path characteristics and deviations can also be quantified through damage surveys. Debris initiation and track information is also a research need of WSE and can be assessed via damage surveys. All of this information would serve to greatly improve engineering-based models of tornadoes and associated perils. This information can then be used to improve understanding of tornado vulnerability. Of perhaps increased importance is the improved understanding of QLCS tornadoes, which haven’t been looked at specifically by WSE. These events appear to be more frequent in the Southeast than a more isolated supercell tornado and if some of these events are being missed or misrated there this is some likelihood that WSE should be designing for these types of events as current wind speed in most of the SE (outside of hurricane-prone regions) is 100-110 mph for most structures.

Comparing methods of wind speed and tornado intensity estimation (e.g., tree-fall patterns vs. EF-scale) using all available methods is a crucial research need. Current databases of tornado intensity are used as a baseline for climatological and meteorological studies and nearly all engineering-based climatological and risk analyses. Recent research has shown that tornado frequency and intensity estimates may be significantly in error (e.g., Potvin et al., 2019). This type of research feeds directly back into the climatological assessments and needs of VORTEX-SE.

Another key component WSE are able to provide is from their participation and coordination on building codes and standards committees. Research from VORTEX-SE funded work (e.g., Satrio et al., 2020) and non VORTEX-SE work (e.g., Kosiba and Wurman, 2013) was utilized in the development of a design tornado wind profile for tornado loading in ASCE 7 and discussions on how tornadic winds are modified in the presence of terrain and topography. The proposal on a tornado wind profile and tornado loading as a whole is still under consideration for the next version of the design standard (ASCE 7-22). Research needs are those that can directly contribute to these efforts which are described in the paragraphs above.

6. Needs: Landfalling Tropical Cyclones

The work in progress likely will produce significantly improved understanding of the conditions that support observed and simulated tornado cyclones in the rainbands of landfalling tropical cyclones, and identify new practices for utilizing CAM models to predict LTC tornado occurrence. It is our assessment that tornado production in LTCs is not significantly different than in most other Southeast tornado scenarios. The environments are characterized by low CAPE (compared to other regions), and very large low-level shear, with the attendant parent storm structures dominated by "mini-supercells" often embedded on other precipitation features. Hence, meteorological focus should be on anticipating this broad class of tornadic storms rather than on unique aspects of LTCs. It is our assessment that specific targeting of meteorological research into LTC tornadoes should be a low priority because of the low probability of significant further advances toward societal application and benefit beyond what will accrue through research in progress.

7. Needs: Forecast Model and Analysis System Improvements

There are few, if any, objective validations of the accuracy and usefulness of CAM guidance in the Southeast. So we must rely on subjective assessments, and in general it seems that CAM guidance must be improved substantially before it can contribute significantly to our situational awareness and threat assessments in the Southeast. This is especially true for issues of timing of the occurrence of convection and the potential for tornadic rotation. Convective mode is perhaps depicted more usefully.

VORTEX-SE is not the most appropriate program for producing improvements in CAM guidance because these improvements involve larger investments in time than can be afforded, and the apparent time horizons for significant progress seem substantially greater than other approaches to improving situational awareness. *This does not diminish the importance of CAM guidance in mitigating the Southeast tornado threat. Thus we view this as a need that is best met through other programs, or coalitions that include VORTEX-SE*.

To the extent that CAM difficulties arise from inadequate representations of the initial state of the atmosphere, a more formal assessment of observing needs is much needed. Even this is relatively expensive, long-horizon work compared to other emphases that might lead to better situational awareness in the near term. However, assessing observing needs perhaps is a logical first step toward CAM improvement. Because VORTEX-SE is already planning to invest significant resources into special observations (and, in fact, has invested in these for over five years), it seems to make sense that further data collection in VORTEX-SE should be done with consideration given concerning the utility of the data in future observing system studies. If VORTEX-SE is to support observing system studies, this too should probably be done in the context of coalitions with other programs. A variety of approaches may all be suitable for these studies, including formal OSSE's, so-called "quick and dirty" OSSEs, data denial experiments, ensemble sensitivity analysis, etc.

It is our opinion that the greatest potential for tornado guidance improvement in the short term may be through the use of Machine Learning (ML). Some of this potential has been demonstrated through VORTEX-SE supported research by Steinkruger et al. (2020). New approaches could consider CAM output, Multi-Radar-Multi-Sensor (MRMS) analyses, 3D-RTMA, and other similar inputs alone or in combination.

Because VORTEX-SE is not well positioned (in terms of the funding levels, reliability of future funding, and expectations) to do additional basic "model engineering" type activities, we are recommending that these sorts of studies be de-emphasized going forward.

4.2 Social, Behavioral, and Economic Sciences Emphases

As with the PS, here we emphasize SBE research needs that are more readily matched to the current two-year VORTEX-SE funding cycle. However, as discussed in Section 4.3, we also advocate additional types and scopes of SBE research that are needed in support of VORTEX-SE's overarching goal.

Below, we summarize research needs in subsections that match the Section 3 research summaries: (1) Vulnerabilities; (2) Risk and Hazard Information; (3) Risk Assessment and Decision-Making; (4) Forecasters and Forecaster / Warning System Partners; and (5) Overlapping, Cascading, and Compounding Tornado Hazards and Risks. Importantly, many SBE research needs cut across these sections *and* should be conducted interdisciplinarily, in conjunction with physical, engineering, and other sciences. We summarize those needs in subsection (6) Interdisciplinary and Cross-collaborative Research between SBE and PS, Engineering, and Other Disciplines.

In synthesizing these SBE and interdisciplinary research needs, we recognize recent past and ongoing related research agenda-setting efforts. Among them are the NOAA-funded consensus study report from the National Academies of Sciences, Engineering, and Medicine that was released in 2017 and is titled, *Integrating Social and Behavioral Sciences within the Weather Enterprise* (NASEM 2017), the NOAA Social Science R2O workshop and report (NOAA 2020), and the updating of the Forecasting a Continuum of Environmental Threats (FACETs) Strategic Implementation Plan. (See also Sections 4.3-4.4). These other efforts identify research needs that have some overlap with VORTEX-SE research needs. Thus, we generally recommend awareness of and synergies with the research needs identified by those efforts, and we have integrated some of the specific research needs into the summaries below.

a. Needs: Vulnerabilities

Vulnerability research is at the center of the VORTEX-SE mission to save lives and reduce the impacts of tornadoes on Southeast populations. As Ashley and Strader (2016) highlights, tornado fatalities per capita have remained constant over the past 30 years after steadily declining throughout the previous 80 years. Also, since 1980, the Southeast tornado fatality rate has slightly increased. Although the advent of modern forecasting, improvement in tornado hazard education, and implementation of the WSR 88-D radar network, etc., are potentially reasons for the historical decrease in tornado fatality rates (Brooks and Doswell 2002), the recent pause or increase in tornado death rates in the Southeast U.S. is thought to be the consequence of a growing developed land use footprint (i.e., the Expanding Bull's Eye Effect; Ashley et al. 2014; Strader and Ashley 2015) and escalating societal vulnerability. Additional research investigating tornado vulnerability and disasters is needed to uncover reasons as to why the Southeast U.S. tornado death rate has increased over the last three decades.

To date, the VORTEX-SE program has placed emphasis on research with some vulnerable populations, such as those living in mobile and manufactured housing, but the research has unfortunately done little to connect with the social, political, and economic contexts of the Southeast that give rise to vulnerability, including the circumstances surrounding how and why individuals live in mobile and manufactured housing to begin with. This limitation ultimately constrains potential applications and solutions that could be developed to address vulnerabilities in the region. Future research should encourage these more community-centered approaches, urging researchers to situate their work within the context of particular places and populations of the Southeast. This could include, for example, detailed studies of post-tornado outcomes in communities with different levels of access to political, economic, or social capital; or generally, studies that consider place as an important frame for understanding and managing vulnerability.

Considering these important contexts, one area of important focus, for example, is highly vulnerable populations such as manufactured/mobile home residents that are most likely to be killed by tornadoes, and what societal factors contribute to the vulnerability of these populations. In the manufactured/mobile example, although only 6% of the U.S housing stock is made up of manufactured/mobile homes, over 50% of tornado-housing fatalities occur in mobile or manufactured homes (Strader and Ashley 2018). The Southeast contains the highest concentration of mobile and manufactured homes and consequently the greatest frequency of tornado fatalities. Together, these statistics point to a need for additional research that examines manufactured homes and their residents from both a physical (structural) and social vulnerability standpoint. Future studies should consider implementing integrated social, physical, and engineering approaches combined with operational practices aimed at improving Southeast community resilience, especially for mobile/manufactured home populations. Research needs including mobile home performance, performance of designated shelters and best refuge areas in tornado events would strike directly at some of these vulnerabilities and act as a first step on how to reduce them for both individual residents and communities at large.

As prior research has identified, there are a multitude of other vulnerable populations aside from mobile/manufactured housing residents that should also be investigated with respect to tornado impacts and disasters. Specifically, there should be an increased focus on Southeast rural populations given that they often lack the resources to properly respond and recover from disasters (e.g., Cutter et al. 2003). In addition, many Southeast regions and counties are still split along cultural lines (e.g., Southern Alabama Black Belt vs. Northern Alabama Hill and Valley Region) that potentially creates barriers during tornado disasters. More recently, there has been an influx of higher densities of Spanish-speaking populations--especially those residing in mobile-manufactured homes (Ash et al. 2020). Altogether, there is a dearth in research focusing on local and regional aspects of social and physical vulnerability as they related to Southeast U.S. tornadoes. Additional research concentrating on how societal vulnerability characteristics such as poverty, race, age, gender, language, disability, household size, etc. influence tornado disaster magnitude and frequency is needed. Research examining spatiotemporal aspects of these vulnerability factors and how they relate to the NWS forecasting process is also encouraged. We further call for this research in subsection 4 below.

b. Needs: Risk and Hazard Information

The VSE-funded research on this theme has begun to offer important insights. Still, there remains a strong need for additional research on this topic, to more robustly know how people access, interpret, and use risk information, including tornado forecast information (including outlooks, watches, and warnings), recommended preparedness and response information, environmental cues, and social cues.

One overarching research need pertains to communication of forecast uncertainty information, including probabilistic information. This topic was called for in the NASEM (2017) report and it intersects closely with NOAA's FACETs (and thus Warn-on-Forecast) initiative, thereby presenting an opportunity to leverage VORTEX-SE work to meet multiple objectives while also focusing attention on how FACETs would affect and work within the populations and forecast and warning systems of the Southeast U.S. More specifically, research is needed to understand whether and how different ways of quantitatively and qualitatively communicating forecast uncertainty are interpreted and used by members of the public; how to effectively communicate individual probabilistic products and collections of products, including collections that span multiple event spaces and time scales (i.e., reference classes); and how to communicate probabilistic and other uncertainty information in concert with legacy deterministic watch/warning systems. Importantly, such research should be conducted through different research approaches (e.g., multiple methods, populations, tornadic scenarios and storm types). For instance, although probabilistic tornado forecast information in concept has the potential to save lives, it is essential to augment experimental research with additional methods to understand how people would interpret and accordingly make decisions in complex, real world situations, in which people must process the probabilistic information in conjunction with other risk information, and make decisions for oneself and family members in the context of their beliefs, experiences, barriers, and so forth.

Additional research needs pertaining to risk and hazard information include the need to better understand the growing constellation of risk information people are accessing, interpreting, and using, including how they are utilizing weather app information (e.g., radar) to assess their risk, and how they access and use information via social media. Relatedly and per the "continuum" aspect of FACETs, it is important to better understand people's risk information behaviors as the tornado risk evolves in the days, hours, and minutes leading up to a tornado event (see Morss et al. 2017). Finally, with ever-increasing technological capabilities, additional research is needed to understand how to effectively visualize tornado risks, including how to represent threats geospatially, how people's place-based knowledge and experiences interacts with their interpretations (e.g., Klockow et al. 2014), and how people interpret the visual representations of uncertainty and the evolution of tornado risks.

Finally, in conjunction with WSE research, research is needed to more deeply understand how people perceive their general risks from tornadoes (versus risks from a given threat), and how risk information can be developed accordingly. For example, it may be useful to develop messages to inform the public about why mobile homes are extremely unsafe, even in weak tornadoes, e.g., how structures are likely to fail, guidance on simple ways they can be strengthened, and benefits in doing so. Developing such risk messages however, requires additional WSE research to accurately characterize these aspects (e.g., requiring accurate knowledge of the 4D near-surface wind field in tornadoes as described above).

c. Needs: Risk Assessment and Decision-Making

The VSE-funded research that fits under this theme has yielded multiple studies, which provide an important foundation. Still, it is essential for additional research to be conducted to better understand how people perceive risks from tornadoes; how they assess what they can do when faced with those risks; what behavioral responses, including protective action responses, they engage in; and how factors such as risk information, vulnerabilities and capacities, barriers and motivations, experiences, and other factors influence these processes.

The VSE studies to date that have examined risk perception have had a particular focus on people’s perceived exposure to tornado risks (e.g., climatologically, seasonally, diurnally). However, risk perception is multifaceted, and additional research should be conducted to better understand how people perceive their susceptibility of being negatively affected, the severity of the negative impacts they may endure, and the negative affective aspects of their risk perception. Moreover, it is important that such risk perception studies do not just examine people’s general judgments of the risk target but also specifically their perceptions of themselves and their family being affected. In addition, a more careful and focused consideration of how specific (risk) perceptions interact with specific information and the shape of that information would provide a more detailed set of recommendations for how to tailor information and messaging based on segmenting a local population into risk perception categories.

Multiple VSE studies have identified that, objectively, there are limited safe sheltering options for many populations and, subjectively, that people feel there is limited, if any, safe place for them to go when tornadoes threaten. This suggests that additional research is needed about people’s perceived self and response efficacy -- coupled with additional research on shelter availability -- to more fully understand the extent of this issue. Such research is particularly important given the current compounding risk of COVID-19 (see also subsection 5 below).

Relatedly, some VSE studies have identified additional barriers people face in obtaining information about and taking protective action in response to tornado threats, yet there is a need to more fully characterize these barriers among different populations in the Southeast and for different types of storm threats (e.g., nocturnal). As reduced efficacy and other barriers are identified, there is a correspondent need for research to identify capacities and to develop and test risk message interventions that could help people overcome these hurdles and reduce their risk of harm. Relatedly, the NASEM (2017) report encourages research on how community- or neighborhood-based weather hazard communication and participation (i.e., crowdsourcing or other processes that focus on exchanging information with key community leaders, gatekeepers, and actors) can enhance group-level adaptive capacity to reduce harm; addressing this need is particularly relevant to and feasible given the focus on the Southeast.

Approaches such as these are important steps in involving the public and allowing for bottom up approaches that involve key knowledge and cultural brokers in enhancing adaptive capacity. At the root of our future approach to collaboration with the public is a commitment to ensure that research is not extractive, allowing the wider public to have a voice in the scientific process. To do so we need to turn back to the community, and have the ability to do so through NOAA's existing network in the Sea Grant Program. Sea Grant previously focused on flooding risk and mitigation activities and much of the learning regarding community engagement, but more importantly, long term commitment and sustainability might be usefully applied to severe storms and the tornadoes they produce as well.

There are interdisciplinary research needs that consider people's risk assessment and sheltering behavior in conjunction with WSE. It is essential to further study, and generalize across populations and tornado scenarios, people's sheltering behaviors and, with this knowledge, to research and identify sheltering optimization for different scenarios in order to enable survivability. Such scenarios include identifying the safest sheltering options given different amounts of time to engage in them, spanning the spectrum from seconds to several hours. Relatedly, because shelter-in-place may be the most sensible (or common) response in many cases, it is essential to determine how to make sheltering-in-place a safe option. Multiple research approaches are needed to robustly develop such understanding and guide policy. For example, agent-based modeling may be useful for dynamically understanding sheltering behavior given different risk parameters, e.g., to simulate different storm scenarios in conjunction with building stock and sheltering options and with coupled simulations of how people assess their risk and engage in sheltering behavior. Empirical research about people's risk assessments and responses are needed to robustly parameterize such models.

However, sheltering can also be about a lack of viable choices because shelters don't exist, mobile homes often don't have shelters, and those who shelter-in place in fragile structures (MMHs) die or are seriously injured. There may be a need for a community needs assessment of sheltering options to ascertain whether viable options exist or not. Identifying weak points in community resilience may help to open lines of community support, For example, in rural areas those in safer housing structures might offer to share safe spaces with other community members whose options are limited. Currently, we advise leaving a MMH, but don't say where to go. This limits options greatly and certainly self-efficacy of preparedness.

Moreover, additional research is needed on the response processes of members of the public across a wider array of tornado events. Most events that receive study involve the most damaging tornadoes, but the events that face residents of the Southeast are often highly conditional, and responses during high-end events may not be representative of tornado responses overall. The success of new technological paradigms, such as those proposed in FACETs, will hinge on the ways they can address public needs for the full set of events they will realistically face. This is particularly true for vulnerable populations who may need more time than traditional warnings offer (Rothfusz et al. 2018). Because vulnerable populations are more likely to be injured or die in a wider array of scenarios, including tornadoes of low or moderate intensity, particular research focus is needed to better understand response processes for these populations.

d. Needs: Forecasters and Forecast/Warning System Partners

Based on the variety of social-behavior and interscience (physical + social-behavioral) research conducted under the VORTEX-SE program over the last five years, there is an increased need for researchers to work with integrated warning team (IWT) partners, including NWS forecasters, local and state emergency managers, and media (TV) meteorologists. Although the demand on many of the IWT partners is high and their time and capacity to participate is limited, those VORTEX-SE projects that have collaborated with IWTs (e.g., work by LaDue, Friedman, Strader, Demuth, Klockow-McClain, and Henderson) have been fruitful. Developing these partnerships has been critical for discovering new methods and knowledge about how populations in the Southeast respond to and recover from tornado disasters. Additionally, research on the IWT has demonstrated how the system works to meet the needs of particular populations and where there are shortcomings in doing so. As such, there is a continuing need for research on IWTs and on developing and strengthening these researcher-with-IWT partnerships.

Additional research is needed to understand how NWS forecasters, emergency managers, and broadcast meteorologists assess and make decisions about communication of tornado risk information. As recommended by both the NASEM (2017) report and per the FACETs SIP, there is a need to better understand how forecasters access, understand, and use probabilistic and deterministic guidance to generate forecast products and message threats, and to understand how they conceptualize and communicate confidence, uncertainty, and risk. Moreover, ongoing and future PS research on artificial intelligence, including machine learning, means that there is a need to understand forecasters' interpretations and uses of this output in conjunction with other guidance and observations they use. Moreover, concepts that are taken for granted, like what counts as vulnerability within a particular County Warning Area or broadcaster's viewing area or what is meant by uncertainty and confidence for different experts and publics, are likewise important to understand when building knowledge about expert decision making. Finally, as the NASEM (2017) report recommends, it is important to understand how forecasters balance the requirements for consistency in messaging with the needs for flexibility to best suit different geographical and cultural contexts. While some expert decision making has been studied in VORTEX-SE, additional research is needed to more fully understand the decision-space, e.g., across geographies, storm types and environments, and other factors.

The FACETs SIP further recommends the need to understand core partner workflow, including: reception, comprehension, perception, and response to a continuum of operational threat-based forecast information and messaging, including, but not limited to, watches and warnings, and related design cues such as the use of colors, icons, scales, and indices; weather forecast criteria for decision-making, especially in the creation of impact-based decision support tools and products; and interpretation and use of probabilistic hazard information across event scales, hazards, and decision contexts.

There is also an increasing need for integrating vulnerability research findings with NWS and IWT partner operations. For example, NOAA and FEMA recommend that people who reside in weak-framed housing or manufactured/mobile homes evacuate their structures for sturdier shelter. As mentioned above, the average warning lead time across the U.S. is 13 minutes, leaving little time for these vulnerable residents to reach shelter outside of their homes. Thus, it is recommended that vulnerable populations strongly consider taking shelter at an earlier time, including potentially upon receiving the tornado watch. However, the watch may be issued hours in advance, making it infeasible for vulnerable populations to drop what they are doing and move to their shelter. Thus, the time period between tornado watch and warning issuance is a crucial moment for vulnerable populations during the tornado hazard event timeline. As noted above in the FACETs section, research on how decision making and the forecast process changes throughout this critical time period is needed. Specifically, work is needed to investigate the potential benefits and advantages of gap-filling products and messaging strategies between the watch and warning issuance time periods. These studies should be conducted collaboratively with PS research (to know what is meteorologically feasible and skillful) and with NWS forecasters and partners, thereby increasing integration and usefulness of the research. More generally, this points to the importance of ongoing discussions among VORTEX-SE researchers from all disciplines and operations, in order to work together to better examine processes and procedures for transitioning SBES research into operations.

e. Needs: Overlapping, Cascading, and Compounding Tornado Hazards and Risks

Increasingly, research about hazards and disasters emphasizes the fact that hazards can co-occur in time and space and that these multi-hazard situations are often analyzed separately, assuming independence from one another in origin and impact (Kappes et al. (2012); Cutter 2018; AghaKouchak et al 2020). Hazards common to the Southeast that need additional overlapping-hazards research include landfalling tropical cyclones, which have several embedded threats like tornadoes, storm surge, and flash flooding. Although some research has been conducted on these threats per explicit calls to do so in the 2018 and 2019 funding calls, little is known about the decision making contexts for the public and for forecasters. Gaps exist in the ways emergency managers, broadcast meteorologists, and other partners assess, make decisions about, and communicate overlapping threats like TORFFs. Additional gaps include public understanding of compound and cascading tornado hazards.

Beyond co-occurring meteorological hazards and the risks they pose, the current the COVID-19 pandemic is a profound example of how tornado risks occur against the backdrop of other risks people face and risk assessments and decisions they make. Specific to COVID-19, little is known about how decisions are being made to open and run public tornado shelters, and how individuals are making decisions about their respective risks of tornadoes and exposure to the virus, especially with respect to those who are vulnerable to health impacts and/or who lack personal shelters.

f. Needs: Interdisciplinary Research between SBE and PS, Engineering, and Other Disciplines for Operationalizing Findings and Societal Benefit

VORTEX-SE is a program with interdisciplinary goals and objectives, but mechanisms to meaningfully integrate physical, social, and operational science are not always straightforward. Although funding calls in VORTEX-SE conceptually encourage interdisciplinary research to address complex issues of tornado risk in the Southeastern U.S., in practice most projects represent interdisciplinarity within broad disciplinary silos--i.e., interdisciplinary projects within either physical or social sciences--rather that projects that truly integrate physical and social science. There are exceptions, of course. Still, there is a need to not only encourage but also incentivize and guide deeper, more meaningful interdisciplinary proposals (see also Section 4.3).

Several models exist for integrating SBE sciences, physical sciences, and practitioner or operational sciences, such as team science (Stokols et al 2008), co-production (Lemos et al 2005), and NSF’s convergence research idea. These models can inform how VORTEX-SE research might enable more comprehensive, integrated research approaches, as well as solution-oriented outcomes that are better suited for operations and policy changes. Peek et al (2020) define “convergence” in ways that dovetail with the interdisciplinary aspirations of VORTEX-SE: “An approach to knowledge production and action that involves diverse teams working together in novel ways—transcending disciplinary and organizational boundaries—to address vexing social, economic, environmental, and technical challenges in an effort to reduce disaster losses and promote collective well-being" (p. 2). Interdisciplinary research differs from cross- or multidisciplinary research, which involve different disciplines that may work *alongside* but not *with* each other. Interdisciplinary research involves an effort to blend practices and co-create research; it may hold the key to unlock some of the most resistant challenges to improving public safety to tornadoes in the Southeast. Yet lack of experience with truly interdisciplinary work--with seeing the ways physical, social, and operational sciences can truly work together and inform one another--can be prohibitive. Thus, exemplars of such projects along with training and mentoring for the VORTEX-SE community may be warranted, along with recommendations of how to do interdisciplinary research at the "working level" (Morss et al. 2018).

Supporting interdisciplinary research is an important lens for addressing two elements -- operationalizing findings and societal benefit -- that are central to achieving the overarching goal of VORTEX-SE, which, as stated in Section 1 is "to reduce damage, injuries, and loss of life from tornadoes through improvements in understanding, forecasting and warning, and communicating risks in ways that support protective decision making. This includes understanding and, where possible, providing recommendations for how to mitigate key vulnerabilities to tornadoes in the southeast US."

There appears a disconnect between this goal and some of the research conducted to date. Although some studies explicitly attempt to connect their work to operational settings or to the objective of minimizing harm, other studies appear to conduct more basic research. Although basic research is essential, explicit articulation of why such research is necessary and how it will lay a foundation for future applied work is important for directly connecting with the VORTEX-SE goals and needs.

Beyond issues of basic science, outcomes of individual grants are not always clearly tethered to societal benefit nor are pathways to solutions (e.g., operational or policy relevance) plausible or encouraged. There are multiple ways this can be addressed. Physical science research can explicitly identify *who* and *what* is exposed to the physical phenomena (e.g., QLCS, terrain-influenced events), which can serve as a bridge to connect with SBE research as well as with NWS and IWT operations. Also, some physical scientists doing physical science work have been placed in the SBE category given the multi-disciplinary nature of their projects, suggesting that future physical science projects utilizes these key individuals to help them shape their projects so that inter-science and cross-collaboration goals can be simultaneously met. Simply, there also is a need for more interdisciplinary research in the VORTEX-SE program, to more effectively "move the needle" in terms of operationalizing results and reducing impacts on Southeast populations and improving community resilience. Connections between researchers and NWS and other NOAA entities are strongly encouraged, as well as with their core partners (e.g., emergency managers, TV/media partners). Key to the application of interdisciplinary research, however, is to also entrain expertise of those beyond NWS and their partners to help ensure that societal benefit and solution-oriented interdisciplinary research is successfully implemented. To do this, researchers could engage policy makers, community organizations, professional associations, elected officials, and other practitioners who have the ability to change resources and infrastructures. How to meaningfully engage these new stakeholders is an important need, and in late 2020 VORTEX-SE is beginning an effort to do this engagement via the NOAA Sea Grant Program. Another idea is for future supported physical science projects to consider inter-science collaborations where SBE researchers could use their observed or modeled data as risk or exposure information to inform SBE investigator-led projects involving spatiotemporal analyses, community surveys, and population interviews. The question of, "How can this data gathered be of use to others within VORTEX-SE?", should be addressed at the proposal level.

Finally, there is a need to develop a type of post-interdisciplinary research capacity to move research into operations (and allow emergent operational challenges to shape interdisciplinary objectives). The recent NOAA workshop in fall 2019 on R2O for social sciences was a promising first step, one that has the potential to elicit tangible mechanisms and pathways between operations and SBS research. More is needed on this front to enable proposal design to reflect such pathways at the outset and for agency mechanisms for and expectations about what is or is not operational (and what it means to operationalize social science). RL levels are useful in transitioning technology but do not have the same promise for all types of SBS or interdisciplinary work.

4.3 Type and Scopes of Research Needed

We reiterate that certain changes to the previous VORTEX-SE grant paradigm will be required going forward. One change involves support of PERiLS research. The analysis of PERiLS data will require several years, with output of new knowledge likely peaking at around five years after the field campaign, but significant findings still possible through ten years. NSSL must consider how the needed research can be supported regardless of any variations or cessation in Congressional appropriations. Further, it is typically true that the platform owners and operators are especially qualified to conduct research utilizing their own platforms, and it may be reasonable to direct some level of funding toward those groups in order to facilitate the post-campaign research.

From the SBE perspective, we draw attention to a NOAA-funded consensus study report from the National Academies of Sciences, Engineering, and Medicine that was released in 2017 and is titled *Integrating Social and Behavioral Sciences within the Weather Enterprise* (NASEM 2017). In this report are recommendations about the types and scopes of SBE research that are needed (Section 5.3 in the report). These recommendations are relevant to VORTEX-SE, and thus we reiterate them here; they include needs for:

- Research that is disciplinary, interdisciplinary within SBE, and interdisciplinary between SBE and atmospheric science and other fields, such as engineering and computer and information science
- Research that is basic, applied, and developmental in nature
- Research that is of different scopes and budget sizes to accommodate different research needs. For instance, larger grants are generally appropriate for interdisciplinary work or for particularly resource-intensive data collection and analysis (e.g., longitudinal studies, ethnographic studies, “big data” analysis). Smaller grants may be appropriate for entraining new scholars into the SBE weather research arena, or for proof-of-concept studies or for honing in on very specific and narrow questions ;
- Research that examines a given topic or event from multiple methodological, disciplinary, conceptual, and sampling perspectives;
- Research that takes a given topic that’s been framed by the meteorological community and reframes it from a SBE perspective. For instance, the related topics of “false alarms,” “over-warning,” and “warning complacency” might be reframed as questions about people’s information access, interpretations, perceptions, responses, and experiences;
- Research that cuts across multiple events, populations, or time, in contrast to research that solves a very specific problem at hand;
- Research that systematically employs in-depth, naturalistic, and engaged methods to investigate the lived weather experiences of people, comparison of cases, and identification of similarity and differences across and within populations;

- Research that goes from “end-to-end,” e.g., that studies operational information that goes into and out of the forecast office; private businesses and media companies that access the information and transmit it to the public in many forms; public officials and managers as mediators of forecast, preparedness, and response information; businesses and members of the public as ultimate beneficiaries; and
- Research that leverages and builds on methods, concepts, and theories from non-weather research, recognizing that hazardous weather is a subset of research on risks, hazards, and disasters. This should include past data collection instruments and datasets that can be mined for secondary analyses.

Augmenting these recommendations from the NASEM report, in order to robustly guide operationalization of results and otherwise guide policy changes, we further recommend that there be conversations among the PS, SBE, and operational groups as well as with NSSL and other NOAA leadership in order to discuss critical issues and criteria for doing so. For instance, what constitutes “societal benefit”, how is this assessed, by whom, and based on what? If research is deemed as making progress toward societal benefit, how can it be further supported while also maintaining support for new research that has yet-to-be-realized potential for societal benefit? When is there sufficient evidence from SBE and interdisciplinary research to warrant operationalizing the findings? What are the different ways (direct and indirect, formal and informal, etc.) that knowledge from SBE research can be operationalized? Initial conversations about some of these questions were had as part of a WPO-led workshop in September 2019 about SBE R2O, and the workshop report offers an important foundation (NOAA 2020). The VORTEX-SE program offers a geographically and hazard-focused opportunity to further these conversations in additional, focused ways.

Finally, a general complaint from VORTEX-SE investigators is that the grant announcements are made after the typical graduate student recruiting "season". This often leads to a lack of progress during the first grant year, and then a struggle to "catch up" in the second year. The grants would be more productive if NSSL were able to communicate likely awards to the investigators around early March in any given year.

4.4 Connections to Other NOAA Efforts

VORTEX-SE is focused on tornado issues of special concern in the Southeastern United States, and there is tremendous value to research that is focused accordingly. Nevertheless, there are other NOAA efforts that are supporting research that is relevant to and should be known and leveraged by the VORTEX-SE program--and vice versa. Among the other relevant NOAA efforts at the time of this writing are programs and funding opportunities for the following: Forecasting a Continuum of Environmental Threats (FACETs) and Warn-on-Forecast (WoF); the Tornado Warning Improvement and Extension Program (TWIEP); the Joint Technology Transfer Initiative (JTTI); the Hazardous Weather Testbed; Social, Behavioral and Economic Sciences (SBES); and Hazard Services. It would be beneficial for many reasons -- economically, to more fully assess and advance knowledge and R2O, etc. -- for there to be stronger connections and communication among these NOAA efforts.

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