VORTEX-SE
Science Plan

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Abbreviations and Acronyms

CAPE Convective Available Potential Energy
FFO Federal Funding Opportunity
LAOF Lower Atmospheric Observing Facility
OFAP Observing Facilities Advisory Panel
PBL Planetary Boundary Layer
PI Principal Investigator
PM Project Manager
SBE Social, Behavioral, and Economic sciences
SSC Scientific Steering Committee
VW Virtual Workshop

1. Introduction to the 2018 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 risk communication 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.

The VORTEX-SE Science Plan is revised annually. In this Plan, the Steering Committee recommends a change of observing campaign policy: unless there are scientific reasons to do otherwise, observing campaigns should span the period October-April. Experience indicates that the majority of severe weather events are missed when campaigns are confined to the March-April period. This new approach means that VORTEX-SE grants should be awarded around July (versus September as in previous years) so that awardees may have time to prepare for field activities that commence around the first of October. In order for NOAA to adapt VORTEX-SE policy and funding announcements to this new approach, Federal Funding Opportunities will be announced around January, and hence this Science Plan must be up-to-date around the beginning of October each year. Hence the next update to this Science Plan will be completed around 1 Oct 2018, and will be referred to as the 2019 Update.

This version of the Science Plan updates the revision generated early in 2017. It reflects the opinions and deliberations of the VORTEX-SE Scientific Steering Committee (SSC) regarding current science issues and priorities. It provides overviews of limited observing efforts to be conducted in March and April 2018, a major observing campaign in October 2018 - April 2019, and a subsequent major observing campaign in October 2019 - April 2020.

In analyzing a variety of issues that impact VORTEX-SE research, the Scientific Steering Committee (SSC) has gained a better understanding of the objectives and constraints of the program, which continually evolve. These are described in Sections 2 and 3 to enable readers to have a better understanding of the decisions made in generating this Science Plan. The approach to identifying the relevant science issues, and the methods used to prioritize the work, are described in Sections 4 and 5. These sections (2-5) are largely unchanged from the previous plan. The current plan for 2018-2021 is described in Section 6, and does embody some significant changes from the previous Science Plan.

2. Objectives

The primary objective of VORTEX-SE is to improve the understanding, detection, forecasting, and warning of tornadoes in the Southeast U.S., and to mitigate the risk posed by these tornadoes through better preparedness, communication, and response. In the first three years of VORTEX-SE, most activities have served to better understand the nature and scope of these problems. As the project continues, it is now possible to identify and prioritize specific topics that require the most urgent attention.VORTEX-SE is quite different than previous VORTEX experiments in that the tornado problem is being examined from “end-to-end”... from fundamental science issues to societal impacts and the use of information by members of the public and other groups. VORTEX-SE is attempting to promote communication and collaboration among researchers and practitioners across this entire spectrum. The primary mechanisms for promoting interdisciplinary work in VORTEX-SE are interactions in our annual workshop and possibly a renewed use of a virtual workshop approach, and incentivizing interdisciplinary projects through agency funding policies.

The experiences in VORTEX-SE indicate that it is not possible to follow a carefully prescribed route to the new knowledge being sought. Instead, we seek to promote a synergism between the collection of the most pertinent data sets, exploration of the issues using combinations of observational and numerical approaches. The Science Plan represents an assessment of the most broadly useful data sets required, the currently most addressable research topics, and a vision of the likely future evolution of both. VORTEX-SE must consider the most efficient use of limited resources to gain knowledge that has a viable path toward beneficial societal application, and thus the project continues to become more focused in terms of scientific scope as well as potential application.

In parallel to physical science research, and often in collaboration, social and behavioral scientists will be investigating key issues related to communication, vulnerability, and the forecast/warning process for tornadoes in the Southeast. This objective will continue to narrow the focus on the most important problems in these areas and address key knowledge gaps. This new knowledge, combined with that being developed about physical science and engineering aspects of Southeast tornadoes and their impacts, will then be used to develop and test recommendations for improving information, approaches, and systems to mitigate the tornado hazard in the Southeast.

3. Planning Philosophy

In planning VORTEX-SE research, several important constraints have been identified by the SSC. The science plan reflects an effort to adjust to, and balance, the often-competing needs and constraints.

Prioritization is essentially a sorting process. Sorting is a simple, well-understood process when one or two criterion are being used for sorting. The process quickly grows intractably complex and expensive as criteria are added, and the dependencies between sorted items come into play.

For example, it is fairly straightforward to sort VORTEX-SE problems by operational importance, or scientific interest, or resource cost, etc. When a number of prioritization criteria come into play, as in Section 5, the problem becomes impervious to an objective solution. Further, in planning VORTEX-SE, we are faced with not only prioritization, but scheduling and sequencing of problems. The only viable solution for this problem is to understand the influences of the various criteria, and arrive at a best subjective consensus assessment. This science plan represents the subjective consensus assessment of the VORTEX-SE Scientific Steering Committee.

4. Approach to revising the Science Plan

The Fall 2017 VORTEX-SE Workshop was held in Huntsville AL in November 2017. This workshop enabled the SSC, VORTEX-SE grantees, and other interested community members to be brought up-to-date on current and planned research and the findings of the working groups. The discussions at this workshop motivated the current VORTEX-SE five-year agenda, and its science topic prioritization, described in this updated Science Plan.

The current set of science questions of most concern in VORTEX-SE are listed in Appendix A. This is a subset of a large group of questions that have been discussed in various fora over the last two years. It must be understood that many questions are not included here. Some were deemed to be best addressed outside the context of VORTEX-SE. Some are not directly relevant to tornado issues. And many simply have not had investigators come forward and advocate for the science issue to the SSC or other VORTEX-SE participants (if we don't know about a science question, it's hard to write about a science question!). With each question, we attempt to give a sense of the priority and scheduling: why the question is (not) in the current science agenda, and if the question is included in the agenda, why it is scheduled for a particular time period. We also attempt to add enough related questions and discussions to inform a potential investigator of the SSC perspective of the science issues involved.

The science questions are often grouped in clusters. We believe that they should be presented to potential investigators in this style so that the investigators can think about ways of addressing entire clusters of related questions simultaneously and synergistically when possible.

These science questions (and clusters) are intended to inform potential VORTEX-SE investigators and funders of what we currently perceive to be the important knowledge gaps. In some cases, general methodological approaches (e.g., observations, modeling) are discussed; however, we anticipate that the research will proceed through investigators and their teams to develop, propose, and then apply the specific approaches and methods that are most appropriate to advance knowledge in each topic area … approaches that the SSC may not be able to specify in advance. We then expect that agency proposal review processes will assess the particular Conceptual Framework (detailed science question, data collection and analyses, etc.) that investigators propose to use to address the larger science question of interest. Hence, the SSC role is simply to determine that *some* Conceptual Framework is likely to exist for each science question or cluster that is included in the Science Plan.

Much of the material in Appendix B was generated in late 2016 through the deliberations of a set of working groups. In late 2017, these working groups were asked to consider the need to update the descriptions of science issues in Appendix B. The output of these fresh looks are summarized at the start of each section in Appendix B.

5. Prioritization and Scheduling

This VSE Science Plan for FY2018 - FY2021 is encapsulated in Table 1. Research questions, or clusters of strongly related research questions, are each assigned a target year for commencement of research. The research topics included in the Science Plan table are those deemed of the highest priority for funding support. The assessment of priority was made subjectively using the criteria described in this section. Each question, or cluster of questions, is described in detail in Appendix A. In those descriptions, the important prioritization and scheduling considerations are described. The Science Plan table (Table 1) depicts the highest-priority research topics as assessed by the SSC, and their sequence of execution. Many other science topics, suitable for investigation in VORTEX-SE but of lower priority, are included in the science topic summaries (Appendix A) and the working group reports (Appendix B). It is assumed that the knowledge landscape will evolve, and that this plan will require an annual re-evaluation of priorities and scheduling.

In many ways, the most difficult task in designing this Science Plan is to determine the most appropriate and effective sequence of emphases. This sequencing is vitally important in the Physical Sciences, where important questions cannot be addressed without certain key pieces of antecedent research being executed. Effective sequencing also enhances the potential for a broader program-wide focus at any given time, which increases the level of collaboration, effectiveness, and efficiency of our research. Once a reasonable sequence of emphases was established, and the reasoning and constraints leading to that sequence was understood, the best level of prioritization often followed. This process of sequencing is reflected in Criteria 2-5 below.

Criterion 1: Operational importance

The dominant considerations in establishing VORTEX-SE research priorities involve current and anticipated operational problems. By “operational” we refer to the flow of information and actions through all of the elements of society and government that can utilize the new knowledge we obtain regarding the Southeast tornado problem. This encompasses obtaining observations; understanding, modeling, and forecasting processes; creating weather information (watches, warnings, probabilistic forecasts, uncertainty); communication of weather information to various publics; and comprehension and response processes in those publics. The SSC has representatives who are well-informed on this entire breadth of operational issues, and provide feedback on research prioritization. *For Criterion 1, the SSC assessed the relevance of a research question based on its operational importance in the shorter term as well as over the anticipated time frame of the VORTEX-SE program (approximately 10 years).*

Criterion 2: Maturity of research conceptual frameworks

In most cases, the SSC believes that mechanisms such as competitive grant processes, workshops, peer and panel review, etc., are the best ways to identify the most promising approaches to addressing the research questions such as those discussed here, and are most likely to promote the intellectual sparks that lead to new discoveries. To identify a topic as a VORTEX-SE research priority, however, the SSC did assess whether adequate research methods are likely to be available for a particular problem, or whether the problem requires further thought or fundamental research outside the context of VORTEX-SE. Adding to the complexity of this prioritization challenge, however, is a recognition that some essential science may not be amenable to formulation of a strong conceptual framework[1]. *For Criterion 2, the SSC assessed whether there are likely to be legitimate conceptual frameworks proposed for answering the research question, and if not, what is the expected path toward progress in answering the question.*

Criterion 3: The funding/research/reporting cycle, and the role of antecedent research

This is an especially strong consideration for areas of research in which preliminary studies are required in order to establish a baseline of knowledge for subsequent studies. More generally, It is an issue of efficiency of the use of resources. The most optimistic timelines in VORTEX-SE involve about four years from planning, through execution, to the transfer of findings to the broader weather and preparedness enterprise. This can be best understood by examining Table 1, described in detail in Sec. 6c. Hence, the most optimistic schedule for revisiting a certain topic, or set of related topics, is once every four years. *For Criterion 3, the SSC assessed whether a research topic should be delayed for consideration based upon the necessity of developing important baseline, contextual, or antecedent information prior to addressing the research topic.*

Criterion 4: Grouping questions to increase the efficacy of synergistic observations and project efficiency

In general, it makes sense that observations -- especially meteorological field observations -- be coordinated in time, location, and for synergistic objectives. This is important to maximize the scientific efficiency of VORTEX-SE by meeting the data needs of multiple researchers simultaneously, and providing contextual data sets for the more-focused investigations. And coordinated focused meteorological observing campaigns can often provide data sets that are sufficiently comprehensive to meet the needs of a researcher who wants to analyze data to explore new (less defined, more unknown) topic areas. (Note that the SSC believes that, under some circumstances, it may be appropriate to cast a broad net without focus on specific phenomena; see Criterion 6).

[1] In this Science Plan, all of the research questions are deemed to have suitable conceptual frameworks available. Some consideration has been given to long-term, fixed-network “fishing expedition” approaches. These are thought to be potentially valuable, and will continue to be scrutinized by the Steering Committee. However, none of these approaches are currently part of the Science Plan.

These concerns argue against scheduling strongly disparate meteorological observing campaigns in a single time period. For example, a field campaign that uses multiple platforms to observe the role of a particular terrain feature in modulating convection might not be compatible with a campaign that explores microphysical processes and lightning, given available resources. Two disparate foci could result in a "subcritical" observing capability in both. Disparate foci also generally lead to resource contention, and not every research problem can survive the impacts of ad hoc negotiated meteorological field data collection strategies. *For Criterion 4, the SSC assessed whether a particular physical science research question can most effectively be addressed by grouping it with similar questions, amenable to focused meteorological observing campaigns.*

These concerns also argue for scheduling compatible physical science, operational, and SBE research during a single time period, to the extent possible. *Thus, for Criterion 4, the SSC also assessed whether an operational or SBE research question could be most effectively addressed by grouping it with a related meteorological observing campaign.*

Criterion 5: Meteorological community facilities require a lengthy planning window

If, for example, LAOF resources are required for a meteorological field observing campaign, there are particular planning windows that are required. In general, about 3 ½ years will elapse between the time VORTEX-SE identifies the need for a large coordinated meteorological observing campaign involving the LAOF, and the execution of that campaign. Hence, the SSC must consider whether to postpone those clusters of topics for that time period, or perhaps to pursue stepping-stone investigations that would improve the chances of NSF support of a large science project via the LAOF.

These large or complex meteorological observing campaigns normally evolve out of a community-identified need for reasonably focused, synergistic field observations. Such observations are generally scientifically important in contexts larger than that of VORTEX-SE, and address questions that require longer timetables to answer, with less operational urgency than typical VORTEX-SE topics. As needs for these larger observing campaigns begin to be identified at the "grass roots", the planning requirements and processes of other agencies (such as NSF and NASA) will begin to come into play, and will almost certainly force adjustments to the prioritization and sequencing of VORTEX-SE physical science. *For Criterion 5, the SSC assessed whether a physical science research question should be pursued via NSF Small or Large Science (or similar approaches in other agencies).*

Criterion 6: Existing data

For Criterion 6, the SSC assessed whether a particular research question can be addressed using existing data that have not been fully exploited. Using existing data is of higher priority than collecting new data sets, for physical science research in particular.

Criterion 7: Feasibility of obtaining needed data

For Criterion 7, for research questions requiring new data, the SSC assessed whether obtaining the required data, whether in physical or SBE research, is currently feasible in the Southeast U.S.

6. Science Plan, FY2018-2022

a. FY2016 Summary

Research underway in 2016 met needs identified by an ad hoc SSC that worked in early 2015, and provided guidance for an April 2015 NOAA/OAR grant competition. Additionally, some NOAA/OAR laboratory projects were chosen prior to the formation of the ad hoc SSC. The 2016 research cast a wide net, from demonstrating and improving NWP approaches, to studying internal storm processes, to preliminary investigations of the functioning of emergency management in potentially tornadic situations.

Early results have been reported from these projects in late October 2016, and at the November 2016 VORTEX-SE Workshop in Portland. These early results have been considered by the SSC in the drafting of this revised Science Plan.

b. FY2017 Summary

The VORTEX-SE Science Plan drafted in late winter 2016 (and called the Science Roadmap) served as a basis for NOAA/OAR funding decisions using funds allocated by Congress in FY16. The resulting grant competition, conducted in the spring of 2016, with awards finalized in September 2016, had a primary physical sciences focus on the role of terrain in modulating the environments of storms and potentially influencing tornadogenesis, and process studies of potentially tornadic storms. Consistent with the state of knowledge of the SBE issues in the Southeast, SBE and operational research goals reflected an emphasis on three broad, foundational themes: understanding and reducing societal vulnerability to tornadoes; operational forecasting and the warning and response system; and risk communication, risk perception, and information use in protective decision making.

The FY16 NOAA grant competition resulted in several funded physical science projects that begin to address the role of complex terrain. At a minimum, wind observations of unprecedented detail were obtained in the complex terrain of northeast Alabama in the spring of 2017 through the use of at least five mobile and one airborne Doppler radar, as well as various other in situ and remote sensors. Other funded activities focused observations on some aspects of storm processes in the Southeast. Several projects focused on operational and SBE aspects of VORTEX-SE were also funded. These projects, in conjunction with ongoing VORTEX-SE research, will continue to develop a basis for conducting additional studies, including work focused more directly on recommending and testing operational improvements, in future years.

c. FY2018

Per the NOAA funding announcement of spring 2017, only very limited observing will be conducted in the spring of 2018. The overarching goal is to demonstrate the viability of combined surface and airborne radar observations and analyses in potentially tornadic convection in the Southeast U.S. As soon as an Operations Plan overview for the Spring 2018 observing campaign is available, it will be included in the Science Plan as Appendix C. Additionally, an overview of expected Meso18-19 Operations will be included in this Science Plan as Appendix D. The next Science Plan update (~October 2018) will include an operations plan overview for studying Non-Classical Tornadic Storms (NCTS19-20).

d. FY2019 and beyond: Research Questions, Timetables, and Prioritization

In the previous Science Plan, the planning needs and timing of possible NSF-supported field campaigns were considered heavily. A general philosophy was introduced that VORTEX-SE research should be aimed at reducing the scientific risk, developing the hypotheses, and improving the likelihood of NSF support for these large campaigns. The initial campaign was dubbed “LowCAPE”, which was an umbrella for a broad set of issues that made forecasting of Southeast tornadoes more difficult, especially in the common low-CAPE high-shear weather regimes. The second campaign that was contemplated was one aimed at understanding the processes in the non-typical tornado producing storms of the Southeast.

Based on discussions of a special planning committee exploring the need for an NSF-supported observing campaign, as well as output of the Fall 2017 Workshop (Huntsville), certain differences between the NSF approach and the VORTEX-SE approach make strongly dependent planning infeasible. VORTEX-SE aims to address science topics that have a clear, expedient route to beneficial societal application. NSF-supported research is often more fundamental and requires more deliberate planning and execution. VORTEX-SE must adjust emphases and plan and execute observing campaigns on 2-3 year time scales, and the larger NSF efforts naturally require longer planning and execution times. These differences imply that the role of NSF-supported observing campaigns in VORTEX-SE should be one of addressing the larger, more fundamental and often more difficult science issues that we are identifying. It is likely that such a campaign will be needed at some point in the future, and when this need emerges, VORTEX-SE should be prepared to adapt and provide synergistic research solicitations and field support. However, the previous Science Plan was built on the assumption of NSF observing campaigns occurring in particular years, and this was not a viable approach.

Hence this Science Plan update takes a somewhat different approach to observing campaign planning and scheduling, while preserving the science emphases of the last version. In response to an analysis by the University of Alabama-Huntsville (Knupp, Lyza; personal communication) that showed that a small fraction of possible tornado events were being observed in the March-April Intensive Observing Periods (IOPs) of 2016-17, the observing campaigns will now generally span the period October-April, subject to constraints such as funding availability, grant administration requirements, availability of required community observation platforms, etc.

The workshop, previous science plans, and SSC conversations have generally identified two broad emphases, as described presently. Under the moniker “Meso”, VORTEX-SE observations will emphasize studies that examine the meso-beta and meso-gamma scale variability of CAPE, low-level shear (e.g. 0-1 km, 0-3 km), and PBL stratification as these impact local tornado potential. This topic emerges from early VORTEX-SE observational studies that establish possible links between particular tornado events and local maxima in CAPE and shear, as well as CAM guidance (e.g. NSSL’s NEWS-e) that depicts significant variations in these parameters on 10’s km scales. Initially, emphasis will be on simply establishing the relevant time and space scales. This will help inform observing strategies for subsequent observing efforts that will delve more strongly into the processes influencing the variability and scales. In a broad sense, synergistic SBE studies might emphasize aspects of preparedness, communications, etc. at time scales of tens of minutes to hours (the watch and outlook time scales in the current nomenclature).

Under the moniker “NCTS” (for Non-Classical Tornadic Storms), observations will emphasize the processes that promote or hinder tornado formation, especially in the context of non-classical storms, low CAPE, and high shear. The NCTS emphasis will include both the storm-scale processes and associated small-scale mesoscale processes. Broadly, this physical science emphasis meshes well with SBE knowledge goals that focus on communication and response during severe weather episodes, especially at the “warning” time scale and somewhat longer.

In FY18 and beyond, it is possible that issues related to tornadoes in landfalling tropical cyclones may garner more attention in VORTEX-SE. The SSC will be working to identify the most important issues, which are likely to include SBE studies of communication and vulnerability in multi-hazard scenarios.

In this Science Plan, it is assumed that the two emphases will alternate during the next four years. However, only the first two campaigns must be firm (owing to NOAA planning and execution constraints). The SSC may change or adapt emphases thereafter based on emerging knowledge and priorities. Because a clear justification for prioritizing one of these emphases over the other did not emerge from SSC discussions, NOAA chose to execute the Meso emphasis in the first long-season campaign (Oct 2018-Apr 2019).

To the extent possible, NOAA will support, via funding mechanisms outside of competitive grant programs, the collection of observations that will be commonly useful to the broad VORTEX-SE research community. An example would be surface mesonet, sounding, and profiler observations under the “Meso” emphasis. This approach is aimed to reduce the risk of heavily redundant observations being supported and coordinated based on the unpredictable success of proposals in a grant competition (e.g. twelve mobile sounding systems when four are needed).

The observing emphases will not be tightly coordinated with the research proposal solicitations because of the extreme impracticality of such an approach. Instead, the approach will be to obtain data sets that are broadly useful for VORTEX-SE research and relevant to the prioritized topics.

Then, via research grants, investigators can explore the previously-collected data, or bring special unique observing capabilities to bear in coordination with the community observations.

The following two tables summarize the research questions currently believed to be most pertinent in VORTEX-SE. To facilitate formatting this material in a readable way in the current version of the Science Plan, one table emphasizes the physical science priorities and timeline and the other the social science and interdisciplinary (physical science - social science - engineering) priorities. In future versions of the Science Plan, we anticipate combining these tables and augmenting them by articulating more coordinated interdisciplinary themes (as reflected in the "planning" column in Table 2).

The rows are ordered by year, and the columns describe different aspects of the program. In Table 1, the columns represent the sequence of program activities, from planning through observation, analysis, and implementation outside the research community. In Table 2, the "year," "planning," "solicit proposals," and "research outcomes and R2X" columns are parallel to those in Table 1. In Table 2, because the activities are less directly tied to planning the specific meteorological observations to be obtained in a coordinated field campaign, the "observation" and "analysis" columns are combined into a single "activities" column (with specific observation and analysis activities to be determined based on what is most appropriate in each topic area).

Year	Planning	Solicit Proposals	Meteorological activities: Observations	Meteorological activities: Analysis	Research outcomes and R2X
2016	Fall workshop	Terrain. Storm processes.	Cold pools. Surface drop-size distributions. Lightning mapping. Mesoscale upper-air.	Data assimilation. NWP resolution. Ensemble prediction. Storm process and lightning studies	
2017	Fall workshop. LAOF project committee monitors science questions and considers NSF observing campaign.	Analyze existing data, with an emphasis on better defining mesoscale variability.. Observation synthesis research (traditional or EnKF). NWP research emph. PBL, free-atmosphere, and microphysics	Cold pools. Surface drop-size distributions. Lightning mapping. Mesoscale upper-air. Terrain-modulation of flow and state.	Data assimilation. NWP resolution. Ensemble prediction. Storm process and lightning studies Mesoscale and PBL studies	Improved CAM and ensemble numerical prediction.
2018	Fall workshop.	Mesoscale observing risk reduction studies.	Limited campaign to assess utility of	Data assimilation.	Improved CAM and ensemble numerical

	LAOF project committee continues. Late summer Science Plan update	Meso18-19 adjunct observations Observing system acquisition and installation (if nec.) Observation synthesis research	combined and airborne Doppler radar data sets in the Southeast. Meso18-19 begins in Fall (see description above).	Ensemble prediction. Storm process and lightning studies Mesoscale and PBL studies Terrain influence studies.	prediction. Characterization of SE US storm processes, cold pools, and lightning. Initial R2O of mesoscale evolution of CAPE
2019	Fall workshop. LAOF project committee continues. Late summer Science Plan update	Analysis of 2018 multi-Doppler data; new synthesis approaches and evaluation. Examination of existing data for multiple purposes, incl. Meso18-19 data. NCTS19-20 adjunct observations. .	Meso18-19 in winter/spring (see description above). NCTS19-20 begins in Fall (see description above)	Mesoscale and PBL studies Terrain influence studies.	Improved CAM and ensemble numerical prediction. Characterization of SE US storm processes, cold pools, and lightning. New approaches for synthesizing and assimilating observations. Initial findings regarding terrain influences.
2020	Fall workshop. LAOF project committee continues. Late summer Science Plan update	Examination of existing data for multiple purposes, incl. Meso18-19 and NCTS19-20 data. Meso20-21 adjunct obs.	NCTS19-20 continues in winter/spring (see description above). “Meso”-emphasis observations begin in fall.	Terrain influence studies. Mesoscale and PBL processes influencing CAPE (“Meso”) NWP issues in the representation of low-CAPE environments.	Initial information about mesoscale evolution of CAPE. Findings regarding terrain influences and their faithful representation in NWP. Improved methods of Doppler wind synthesis
2021	Fall workshop.	Examination of existing data for multiple purposes, incl. Meso18-19, NCTS19-20, and Meso20-21 data. NCTS21-22 adjunct obs	“Meso”-emphasis observations continue in winter-spring “NCTS”-emphasis observations commence in fall.	Processes influencing CAPE. Environments of nocturnal, HSLC, and other lowCAPE phenomena. NWP issues in the representation of low-CAPE environments. NCTS process studies	Understanding of mesoscale processes, PBL and aloft, influencing CAPE transferred to ops. Improvement of PBL representation in NWP. Assessment of free-atmosphere issues. Possible mesoanalysis tool improvements
2022		Examination of existing data for multiple purposes,	“NCTS”-emphasis observations continue in winter/spring.	Processes influencing CAPE.	Understanding of mesoscale processes, PBL and aloft,

		including already-concluded Meso and NCTS campaigns.		Environments of nocturnal, HSLC, and other lowCAPE phenomena. NWP issues in the representation of low-CAPE environments.	influencing CAPE transferred to ops. Improvement of PBL representation in NWP. Assessment of free-atmosphere issues. New radar diagnostics for storm processes

Table 1. Table showing the likely progression of physical science planning, execution, and results over the next five years in VORTEX-SE. The columns are described below. The green font denotes topics related to the mesoscale variability emphasis, blue denotes the terrain emphasis, and red denotes storm process studies emphasis. Black font typically denotes activities related to improving the use of NWP in forecasting and informing observing strategies. "MesoMM-NN" denotes a field program to investigate a variety of issues related to the spatial and temporal variability of CAPE, shear, and PBL stratification as these modulate local tornado potential. "NCTSMM-NN" denotes a field program to investigate issues related to processes in non-classical tornadic storms in October of year MM through April of year NN. "R2X" means the transfer of research findings into the broader community of the weather and preparedness enterprise.

Year	Planning	Solicit Proposals	Social science, engineering, and interdisciplinary activities	Research outcomes and R2X
2016	Fall workshop	Understanding and reducing societal vulnerability to tornadoes Research on operational forecasting, NWS partners, and the warning and response system Risk communication, risk perception, and information use in protective decision making	Continue building baseline knowledge in 3 theme areas across SE tornado situations, including key differences between the SE and other regions	
2017	Fall workshop. LAOF project committee monitors science questions and considers NSF observing campaign Articulate interdisciplinary themes	Vulnerability: - Intersections among contributing factors - Adaptive capacities - Survivability Operational processes and warning system: - Forecasters' and interpretations and use of information - Uncertainty and information gaps Risk communication and protective decision making: - Information interpretations and uses - Intersections among information, decisions, and vulnerabilities/capacities	Continue building baseline knowledge in 3 theme areas across SE tornado situations, including key differences between the SE and other regions	Improved knowledge about vulnerability, operational processes and warning system, and risk communication and decision making factors contributing to loss of life from tornadoes in the southeast.

2018	Fall workshop: continue interdisciplinary discussion, consider capability for for rapid-response multi-disciplinary event analysis. Begin integrating social science and interdisciplinary knowledge and identifying key R2X gaps. LAOF project committee continues.	Vulnerability: - Intersections among contributing factors - Adaptive capacities - Survivability Operational processes and warning system: - Forecasters' interpretations and use of information - Uncertainty and information gaps Risk communication and protective decision making: - Information interpretations and uses - Intersections among information, decisions, and vulnerabilities/capacities	Continue building baseline knowledge in 3 theme areas across SE tornado situations Work that: - connects across at least 2 of the theme areas	Improved knowledge about key vulnerability, operational processes and warning system, and risk communication and decision making issues contributing to loss of life from tornadoes in the southeast, and about potential ways to reduce vulnerability and harm.
2019	Fall workshop. LAOF project committee continues.	Vulnerability and risk communication: - Key intersections contributing to harm - Develop and/or test evidence-based recommendations for protective action or policies to alleviate vulnerabilities Operational processes and warning system: - Develop and/or test evidence-based recommendations for improving forecast and warning processes, warning system products and communication, filling key forecaster information gaps	Continue building knowledge in 3 theme areas, refining research foci based on findings to date Work that: - connects across at least 2 of the theme areas - translates social science and interdisciplinary findings into evidence-based recommendations	Improved knowledge about key vulnerability, operational processes and warning system, and risk communication and decision making issues contributing to loss of life from tornadoes in the southeast, and about potential ways to reduce vulnerability and harm.
2020	Fall workshop. LAOF project committee continues.	Vulnerability and risk communication: - Key intersections contributing to harm identified in prior years - Develop and/or test evidence-based recommendations for protective action or policies to alleviate vulnerabilities Operational processes and warning system: - Develop and/or test evidence-based recommendations for improving forecast and warning processes, warning system products and communication, filling key forecaster information gaps	Interconnections with LowCAPE field program: focus on cold season and/or nocturnal, connect social with physical science Work that: - connects across at least 2 of the theme areas or across these themes and physical sciences - develops and/or tests evidence-based recommendations	Improved knowledge about key intersections contributing to harm. Evidence-based recommendations for improving warning process and systems, alleviating vulnerabilities, and improving risk communication and protective decisions.

2021	Fall workshop.	Research to refine knowledge in key areas identified by research to date Develop and test evidence-based recommendations for reducing harm from SE tornados, integrating across multiple VORTEX-SE areas	Interconnections with LowCAPE field program: focus on cold season and/or nocturnal, connect social with physical science Work that: - connects across multiple program areas - develops and/or tests evidence-based recommendations	Improved knowledge about key intersections contributing to harm. Evidence-based recommendations for improving warning process and systems, alleviating vulnerabilities, and improving risk communication and protective decisions.
2022		Research to refine knowledge in key areas identified by research to date Develop and test evidence-based recommendations for reducing harm from SE tornados, integrating across multiple VORTEX-SE areas	Interconnections with NCTS Work that: - connects across multiple program areas - develops and tests evidence-based recommendations	Improved knowledge about key intersections contributing to harm. Evidence-based recommendations for reducing harm from SE tornados.

Table 2. Table showing the anticipated progression of social science, engineering, and interdisciplinary planning, execution, and results over the next five years in VORTEX-SE. The columns are described below.

These tables do not endeavor to list the science questions of Appendix A, but instead to encapsulate them in some broader descriptions. The tables are described in more detail below in Secs. 6d-g following a description of some broader features.

The initial threads of VORTEX-SE arose through the first three NOAA Federal Funding Opportunities (FFO; spring 2015, 2016, 2017). Those funding opportunities in the physical sciences were generally focused on storm process studies, cold pool characterization, and mesoscale low-level evolution. The solicitations in the SBE sciences were aimed at establishing initial knowledge in key topics related to vulnerabilities to tornadoes, tornado warning processes and systems, and interpretations of and responses to warnings (including issues associated with nocturnal tornadoes, false alarms, etc.) that are important components of the loss of life from tornadoes in the southeast US.

In Table 1, different “threads” of physical science emphasis, or overarching themes, are apparent, as denoted by the font color highlights. For example, the NCTS studies thread (red) first entered the planning stages at the start of VORTEX-SE, and will work its way to R2X around 2018-2020. Meanwhile, based in initial findings, this NCTS study thread re-enters planning around 2019-2020 as a field program and once again starts advancing through the planning-execution-results process.

Two field observing campaigns in the Physical Sciences (2016, 2017) were driven by the successful research proposals in the first two FFOs. The SSC maintains the opinion that VORTEX-SE faces some significant observing challenges such as mobility, radar horizon issues, etc., that require additional research and brainstorming before new meteorological observations are attempted. Related to this, a simple understanding of the scales involved in relevant atmospheric phenomena is lacking, and this information is needed to inform improved observing

strategies. In VORTEX-SE we are still trying to ascertain what the optimal approaches to physical science research are, given the fairly extensive list of new and difficult research problems. In light of these concerns, there is a general consensus that the focus should continue to be on physical science problems that are scientifically tractable at scales that are observable. This will pose special challenges for planning the field programs under the NCTS umbrella.

It should be noted that commencing in 2018, a physical science and operational research thread (green in Table 1) begins to emerge with the overarching theme of "Meso". This umbrella includes many of the very-problematic forecasting issues in the Southeast: tornado probability in low-CAPE environments (e.g. CAPE < 800 J kg^{-1}) such as during the cold season and at night, inhomogeneities in tornado potential related to inhomogeneities in (small) CAPE, forecasting these environments, and a number of related issues. The "Meso" emphasis will include field observing campaigns, first in Oct '18 - April '19, and then perhaps again in Oct '20 - April '21, depending on the evolution of this Science Plan.

As the "Meso" thread advances, we commence a return to focus on meteorological processes of special significance in Southeast tornadic storms, which we dub "Non-Classical Tornadic Storms" (NCTS), with field campaigns under the "NCTS" moniker in Oct '19-Apr '20, and perhaps again in Oct '21-Apr '22. Here, NCTS refers to storm morphologies that differ from the classic supercell, which are relatively well understood already from a physical science perspective. These modes include tornadic quasi-linear convective systems, which occur in a distribution of environments shifted toward lower CAPE and higher shear compared to supercells. Further, supercell structures can be short-lived, quickly evolving, and embedded in convective systems that do not have clear linear structure. The NCTS focus is not meant to imply that tornadic supercells are not important in the Southeast; indeed, the majority of tornado deaths in the Southeast are associated with supercells. However, we believe physical science research on classic supercells can be most effectively performed in other regions, and the knowledge gained about supercells in those regions appears to apply quite effectively in the southeast, at least in terms of having reasonable outlooks days in advance of most major supercell outbreaks and having warnings in place for most of the deadly tornadic supercell storms. Conditions for NCTS tornadoes are much more difficult to predict days in advance, and we struggle to distinguish tornadic and non-tornadic NCTS systems to provide accurate warnings. Thus, the NCTS tornadoes contribute to the high false alarm rate in the region even as some NCTS tornadoes are missed. The success of this second major thread of VORTEX-SE will depend on addressing some critical antecedent issues related to obtaining the most useful meteorological observations. An important example of these antecedent needs would be to determine if a dense network of Doppler radars can answer significant questions (i.e., are the most important processes so close to the ground that no reasonable Doppler network can effectively observing them?), or are we just going to have higher-resolution looks at processes that remain mysterious?

In order to be most effective, the "Meso" and NCTS threads both involve the need to establish new baseline information regarding both meteorological observing challenges and NWP capabilities. Hence, it is important to support this baseline research in advance of the field phases, and to the degree possible, before major planning has been completed.

The NCTS thread likely will include new examinations of the interaction of up- and downdrafts in these storms, and the associated lightning patterns. Studies of this type critically depend on our ability to diagnose velocity from observations in complex terrain, a capability that we are trying to establish through currently-supported VORTEX-SE research. This problem may be alleviated somewhat through the incorporation of airborne Doppler radar into the observational mix because of the ability to see “down into” terrain that is obscured from the surface observing perspective (a capability that we will be assessing in March-April 2018 using the NOAA P-3 platform). The NCTS thread should also benefit from new approaches to in situ observations of buoyancy gradients aloft that are currently being explored outside the context of VORTEX-SE.

As shown in Table 2, social science, engineering, and interdisciplinary research will initially proceed within the same three thematic areas as in FY2017: understanding and reducing societal vulnerability, operational processes and the warning system, and risk communication and protective decision making. As VORTEX-SE progresses, this work will evolve into addressing more focused research questions identified in the initial program years, connecting across the three social science / engineering / interdisciplinary themes, and translating findings into evidence-based recommendations for improvements in policies, operational processes, and risk communication. Table 2 also indicates an increased emphasis on interdisciplinary work as the program progresses. For example, during the years of the “Meso” field programs (e.g., FY2019, perhaps FY2021), the social science, engineering, and interdisciplinary work will also include an emphasis on interconnecting with the themes of the physical science, i.e., cold-season and nocturnal tornadoes, and bridging across fields contributing to VORTEX-SE research. In FY2021-22, these efforts will continue to connect across multiple program areas, and to use results from earlier social sciences, engineering, and interdisciplinary research to develop and test evidence-based recommendations for reducing harm from tornadoes in the Southeast U.S.

In the vulnerability theme, work in FY2018-19 emphasizes three subareas: 1) investigating how physical, social, and economic factors interact to contribute to harm from tornadoes in the Southeast, 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 Southeast; and 3) understanding the factors and decisions that enhance individual survival of tornadoes under different circumstances. Building improved understanding in area #1 is 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.

In the risk communication and protective decision making theme, work in FY2018-19 emphasizes: 1) 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; and 2) investigating intersections among information (including probabilistic or uncertainty information and visualizations), vulnerabilities and capacities, and protective decision

making. This work will provide an important foundation for investigating more specific research questions and developing and testing recommendations for improving risk communication and protective decision making in subsequent years of the program.

In the operational processes and warning system theme, FY2018-19 emphasizes: 1) investigating forecasters' interpretations and use of different types of information in decisions about whether, when, and how to issue warnings and other products; and 2) understanding how uncertainty affects the forecast and warning process (for forecasters at national and local offices, as well as with partners) and information gaps that contribute to uncertainty. This work will provide improve understanding of the interplay between probability of detection and warning lead time, as defined by the NWS, for Southeast tornadoes. It will also provide important knowledge for prioritizing physical science research and observations, and for developing and testing recommendations for operational improvements in subsequent years of the program.

In the next two years, the vulnerability and risk communication themes will merge, with an emphasis on: 1) building in-depth understanding of key intersections contributing to harm identified in prior years; 2) developing evidence-based recommendations for policies to alleviate Southeast tornado vulnerabilities; and 3) utilizing the findings of the vulnerability research to develop evidence-based recommendations for the best protective actions for members of the public to take under different circumstances. The operational processes and warning systems theme will emphasize developing evidence-based recommendations for 1) improving forecast and warning processes; 2) improving forecast and warning products and communication, within the NWS and across the weather enterprise (e.g., forecasters, media, public officials), and 3) integrating with physical science to develop recommendations for filling key forecaster information and knowledge gaps. Where appropriate, this work will be integrated with the planned FY2019-20 LowCAPE field campaign and will pilot test recommendations when possible.

In subsequent years, social science, engineering, and interdisciplinary research will emphasize refining knowledge in key areas identified by work to date, and on integrating across multiple VORTEX-SE areas to develop and test evidence-based recommendations for reducing harm from Southeast tornadoes. This will include, as appropriate, engaging emergency managers, planners, and other policy makers at the local, state, and federal levels to discuss emerging findings and and further develop recommendations to reduce damage, injuries, and loss of life from tornadoes.

The tornado issues of concern in the Southeast U.S. intersect across multiple areas, including physical science, social sciences, engineering, public policy, and operational forecasting. Thus, to reduce the loss of life and harm from tornadoes in the Southeast, work is needed that integrates physical sciences, social sciences, and engineering, and that links research to public policy and forecast operations--in other words, work that is truly end-to-end. As a result, interdisciplinary as well as disciplinary research will be critical to achieving the goals of VORTEX-SE. Due to the significant knowledge gaps related to Southeast tornadoes and the initial funding, in the first two years the program has focused primarily on building critical knowledge within specified topic areas. As discussed above, as the program progresses it will continue targeted research in key areas. Importantly though, the future of the VORTEX-SE program also will include research that

explicitly links across multiple topics to develop knowledge and recommendations that can improve warnings, communication, and protective decision making when tornadoes threaten, and help alleviate key vulnerabilities to tornadoes in the southeast US. As indicated in Table 2, we anticipate that one emphasis of VORTEX-SE discussions and revision to the Science Plan in future years will be articulating interdisciplinary research and research-to-operations themes.

One interdisciplinary theme to be more fully developed in future years is developing mechanisms for designing and funding coordinated data collection and analysis focusing on key societal questions for one or two Southeast tornado events. This would include multiple research teams (multiple social science fields, plus engineering and/or physical science as appropriate) investigating interlinked questions using multiple research strategies methods.

6.d Planning Activities

The first column in Tables 1 and 2 describe planning activities required in order to execute the Science Plan. We envision continuing to hold an annual workshop in October or November of each year. The workshop emphasis will be to share findings from recently completed research, or work in progress, as well as plans for newly funded research. The overall science plan, and future needs for concentrated observing campaigns, will be drafted prior to the workshops, and then undergo final revisions based on the reported progress and emerging new ideas. The VORTEX-SE Project Manager (Rasmussen) is exploring new avenues to put some of these efforts into a Virtual Workshop to allow the community to be involved in the planning processes at their convenience and throughout the year.

In Jan 2018, the VORTEX-SE Project Manager began to assemble committees to generate science plans for the informal Spring 2018 activities in VORTEX-SE, as well as the Oct 2018 - Apri 2019 Meso18-19 field campaign. A draft operations plan summary for Meso18-19 is included in this Science Plan (monitor Appendix C for availability). Also in early 2018, the Project Manager will assemble a committee to generate documentation (experiment design, scientific overview, operations plan) for the Oct 2019- Apr 2020 NCTS19-20 campaign. This documentation will be needed by NOAA to guide the development of the next Federal Funding Opportunity announcement in early fall 2018, in order to have grants related to NCTS19-20 awarded by summer 2019, in advance of the beginning of observations in Oct 2019.

6.e Grant Solicitation Activities

The second column in Table 1 encapsulates the recommended topics for physical science *funding emphasis* in any solicitation during the given year. The goal here is to have grants in place to 1) provide timely initial information to aid in planning meteorological field campaigns and future research; 2) support analysis of previously collected meteorological data; and 3) support the collection of meteorological observations in field campaigns in the subsequent year. The topics recommended for funding can be explored further by examining Appendix A (Descriptions of

Research Questions Currently Pertinent in VORTEX-SE) and Appendix B (Working Group Reports).

6.f Meteorological Observing Activities

The third column in Table 1 describes the anticipated meteorological observations to be collected during the calendar year. As described previously, VORTEX-SE observing campaigns will generally span the period October-April to obtain data sets more representative of the unique and difficult forecast environments of tornadoes in the Southeast.

Several items deserve additional comment. First, no VORTEX-SE meteorological observations are planned for CY2018 except for ongoing year-round target-of-opportunity observations at the University of Alabama-Huntsville. In addition, the NOAA P-3, and coordinated SMART-Radar mobile Dopplers and University of Louisiana-Monroe S-band dual-polarimetric radar will be utilized in March and April 2018 to do studies assessing the usefulness of combined airborne/surface Doppler networks in the Southeast. This “down year” was required to better assess the meteorological data sets obtained in 2016 and 2017, and provide much-needed new information to guide the planning of the Meso and NCTS campaigns.

6.g Meteorological Analysis Activities

These activities, in the fourth column of Table 1, are based on the anticipated grants funded in the prior 1-2 years, as well as the anticipated field observing campaigns. This column should be considered to be descriptive of anticipated research based on the previously-collected observations and anticipated progress.

Appendix A. Descriptions of Research Questions Currently Pertinent in VORTEX-SE

This appendix is provided so that potential investigators as well as funding agencies can gain a sense of particular research questions in VORTEX-SE and their prioritization. The questions were culled largely from the 2016 Working Group activities and reports (see Appendix B), as well as from other sources such as the previous Science Roadmap. The list is expected to evolve as new knowledge becomes available, perhaps shifting program priorities and objectives. VORTEX-SE is open to considering problems not included in this list, and encourages all interested researchers to be involved in the science planning process.

A.1 Research Questions Related to Operational Processes and Outcomes

In large part, these questions arise from the working group report in Appendix B.1.

OP1: ***How do forecasters choose guidance to consider? How do they use the guidance? How do they learn to understand guidance, including plausibility, and how do they decide whether to trust and adopt new model information?***

Source: These questions are explained in detail in the working group report on Improving Operational Processes and Outcomes (Appendix B). Quoting:

- What storm-scale (ensemble) information forecasters currently use and how, what information they need, and key operational problems, for example:
    - what model ingredients, parameters, and features (e.g., updraft helicity, tornado formation, tornado tracks, storm composite parameters) and what thresholds (e.g., updraft helicity > 45 m^2s^{-2}),
    - how forecasters interpret and use probabilistic, post-processed guidance from ensembles
- How forecasters combine and use different storm-scale guidance in their forecast process, including ingredients and feature-based guidance, and deterministic runs from ensembles coupled with probabilistic guidance
- How forecasters' interpretations, uses, and operational problems vary across different forecast time periods (0-3 hrs, 3-6 hours, 6+ hours, etc.) and scenarios (seasons, regimes, convective mode, etc.)

Priority: *High in regions with tornado problems*. This research is important to increase the return on investment (better forecast quality) in NWP techniques. This is probably a national concern when all weather hazards are considered.
Recommended timetable: *Continuous*. There are no clear reasons that this question should be sequenced relative to other questions, or grouped for simultaneous execution. One could argue that we should learn how to use current state-of-the-science NWP products before developing new ones, but perhaps the best practical approach is to do this in parallel with NWP techniques development.
Related activities: Romine et al. object-based ensemble characterization.

OP2: ***How is CAM guidance subjectively and objectively verified?***

Source: These questions are explained in detail in the working group report on Improving Operational Processes and Outcomes (Appendix B). Quoting:

- How verification is conceptualized and measured differently and similarly by model developers versus forecasters, and how this shapes (and constrains) model improvement, use, etc.
- How forecasters subjectively "verify" model output in conjunction with available observations to assess its real-time utility
- How forecasters subjectively "verify" model skill post-event
- What objective verification of deterministic and probabilistic guidance forecasters currently use and what information is needed, including verification segmented by region and forecast scenarios (seasons, regime, convective mode, etc.)

- How to provide objective verification information (and training information as needed) in ways that are readily understandable by and accessible to forecasters to best meet their needs

Priority: May not be a high priority exclusively for VORTEX-SE; more of a priority across all regions with convection weather hazards.
Recommended timetable: *Not specific*. There are no clear reasons that this question should be sequenced relative to other questions, or grouped into a cluster for simultaneous execution. It would be potentially beneficial if this topic were executed collaboratively with research into objective CAM verification.
Related activities: This may be a topic that should be combined with NWP objective model assessment research.

OP3: ***What approaches are best in assisting forecasters with identifying and accessing appropriate guidance in the relatively rare meteorological situations?***

Source: These questions are explained in detail in the working group report on Improving Operational Processes and Outcomes (Appendix B). The working group envisioned a technological solution for this problem:

> … there is a need for well-organized, well-visualized, regularly updated repository of model information. This repository might include different models and the products available from them (and possibly information on latest model updates); objective verification information; and training. It might also be developed to be a "smart" repository, e.g., that does initial filtering of an event to diagnose key characteristics (e.g., storm mode) and then tailors the available model guidance accordingly.

How to develop a tool like this could be the subject for additional research.
Priority: May not be a high priority exclusively for VORTEX-SE; more of a national concern.
Recommended timetable: *Not specific; one time*. This question could probably be answered in a single research project.
Related activities:

OP4: ***How is/should forecast uncertainty information be communicated between NWS and its partners? What do various terms such as "confidence", "certainty", and "uncertainty" mean to the parties?***

Source: These questions are explained in detail in the working group report on Improving Operational Processes and Outcomes (Appendix B). Specific elaboration on these questions, extracted from the report, includes:

- When and how forecasters use different storm-scale ensemble guidance and/or other probabilistic tools (ProbSevere, PHI) to communicate with their partners (media, EMs, etc.)
- How forecasters convey uncertainty (both in the warning and outlook time scales) when dealing with frequent "conditional" environments (e.g., HSLC environments) in which

there is high end severe/tornado potential if a severe storm occurs, but with a low probability of an actual event
- Different partners' needs for what type of information, at what time, for what protective action purpose (and what is the range of those actions)
- How partners (e.g., EMs) might ascertain a non-event prior to their NWS partners, and how this gets negotiated
- What does confidence mean as an affective dimension of severe weather threats versus something like a range of possibilities, both in assessments of models but in communications with others (e.g. partners, schools, politicians, etc)?
- What do EMs mean when they ask for forecaster confidence? What do forecasters mean when they use this term individually or collectively? How does it differ from other kinds of confidence (e.g. confidence intervals, probabilistic information, trust, etc.)?
- How do uses / understandings of confidence change for different kinds of events or different temporal and spatial scales?
- When does a forecaster feel certain as evidenced by their taking action or making strong claims? What tools, experience, office procedures, and/or other factors come together to create certainty?
- How are forecasters "teaching" their partners about how to read uncertainty claims. Where are there misunderstandings? What does effective communication of uncertainty look like?

Priority: May not be a high priority exclusively for VORTEX-SE; more of a national concern.
Recommended timetable: It seems that this information should be gathered/studies fairly continuously as the hazard uncertainty communication landscape evolves.
Related activities: Work by LaDue and collaborators.

A.2 Research Questions Related to Risk Perceptions and Communications

In large part, these questions arise from the working group report in Appendix B.2.

RI1: ***How do individuals reflect on the outcomes of previous emergency weather decisions, how does that reflection impact future decision processes, and for how long?***
Source: The source of this questions is the Working Group report from the group on risk perception and communications.
Priority: Not clearly assessable relative to other questions.
Recommended timetable: Short-term
Comment: This question falls under a major theme "Is complacency an individual or group-level trait, and can complacency be mitigated through the experiences of decision-makers or decision-followers within these groups?

RI2: ***How are decisions of caregivers (those directly responsible for the safety of others) influenced by the caregiver's experience and the experiences of others in their care?***

Source: The source of this questions is the Working Group report from the group on risk perception and communications.
Priority: Not clearly assessable relative to other questions.
Recommended timetable: Short-term
Comment: This question falls under a major theme "Is complacency an individual or group-level trait, and can complacency be mitigated through the experiences of decision-makers or decision-followers within these groups?

RI3: ***How can post-crisis information be spread to leverage relevant narratives of care-givers and care-receivers to improve compliance with future emergency weather information?***
Source: The source of this questions is the Working Group report from the group on risk perception and communications.
Priority: Not clearly assessable relative to other questions.
Recommended timetable: Short-term
Comment: This question falls under a major theme "Is complacency an individual or group-level trait, and can complacency be mitigated through the experiences of decision-makers or decision-followers within these groups?

A.3 Research Questions Related to Societal Vulnerability and Refining the Understanding of the Southeast Tornado Problem

In large part, these questions arise from the working group report in Appendix B.3.

VU1: ***How and why do vulnerabilities at the local scale differ from the better-understood vulnerabilities at the regional scale?***
Source: The source of this questions ER's rough condensation of a discussion by Walker Ashley and Stephen Strader in the Working Group report on vulnerability.
Priority: Not clearly assessable relative to other questions.
Recommended timetable: Not specified

VU2: ***What factors increase survivability for those directly impacted by tornadoes (focus on success instead of the causes of injuries and fatalities)?***
Source: The source of this questions ER's rough condensation of a discussion by Walker Ashley and Stephen Strader in the Working Group report on vulnerability. Some of the aspects described include

- Sprawl and unencumbered development
- Building codes (adoption and enforcement)
- Population density
- Proliferation of vulnerable housing stock

Priority: Not clearly assessable relative to other questions.
Recommended timetable: Not specified

VU3: ***What is the climatology of fatal tornadic events by storm type and time of day? What are the unique aspects of nocturnal tornadoes leading to higher mortality? How does human behavior differ in nocturnal events vs. daytime?***
Source: The source of this questions ER's rough condensation of a discussion by Kelsey Ellis in the Working Group report on vulnerability. Some of the aspects described include

- Warning likelihood at night vs. day
- Structures in use vs. time of day
- Availability of visual signals

Priority: Not clearly assessable relative to other questions.
Recommended timetable: Not specified

VU4: ***How do tornado warning statistics and casualties differ in the Southeast compared to other regions?***
Source: The source of this questions ER's rough condensation of a discussion by Dan Sutter in the Working Group report on vulnerability. Some of the aspects described include

- Larger FAR -> fewer fatalities
- Long lead times (> 20 min) are much more beneficial in the Southeast
- Have these findings persisted in the era of impact-based warnings?
- What are the operational circumstances leading to unwarned tornadoes?

Priority: Not clearly assessable relative to other questions.
Recommended timetable: Not specified
Comment: As one perspective, we should consider these questions in terms of optimal ways to translate tornado probabilities into appropriate messages.

VU5: ***Do recurrent false alarms cause tornado-related deaths/injuries, or is the correlation produced by a confounding factor (or set of factors) that causes* both *false alarms and tornado-related deaths/injuries (e.g nocturnal tornadoes)? What is the relationship between* perceptions *of warning system reliability versus actual warning system reliability?***
Source: The source of this questions ER's rough condensation of a discussion by Joe Ripberger in the Working Group report on vulnerability. Some of the aspects described include

- FAR cannot be considered in isolation from other aspects of warning performance
- Don't know how responses are connected to warnings
- Are *perceptions* about warning quality more important than warning quality?
- What are the operational circumstances leading to unwarned tornadoes?

Priority: Not clearly assessable relative to other questions.
Recommended timetable: Not specified

VU6: ***Population, housing, and other characteristics are proxies for potential to suffer harm, but what are the circumstances of individuals who are harmed that give rise to the***

validity of these proxies? What is the role of social networks in transmitting safety, forecast, and warning information?
Source: The source of this questions ER's rough condensation of a discussion by Heather Lazrus and Rebecca Morss in the Working Group report on vulnerability. Some of the aspects described include

- Complex social relationships and networks influence potential for harm

Priority: High
Recommended timetable: Not specified

A.4 Research Questions Related to Atmospheric Processes

In large part, these questions arise from the working group report in Appendix B.4.

PH1: ***What processes control downdrafts in low-CAPE environments? What is the relationship between the downdraft and environment measurables?***
Source: The source of this question was the working group on the use of existing operational data. However, it did not really make a connection to operational data sources, so it was moved to the Atmospheric Processes section.
The discussion included comments on

- The need for CASA-style networks to gain understanding of low- and mid-level processes.
- The necessity of studying non-supercell cases and null cases.

Priority: Low-moderate, becoming high when observing systems and strategies are identified to address the specific questions
Recommended timetable: Good candidate for NCTS field program

PH2: ***What are the dominant modes of tornado formation within quasi-linear convective modes in the Southeast?***
Source: This is leftover from the previous work plan and not something that was emphasized in the 2016 working group.
Priority: Med/high(?) for VORTEX-SE since ratio of QLCS to supercell tornadoes is relatively high in Southeast compared to the Plains.
Recommended timetable: Long-term given multiple years of sufficient field observations.
Related activities: Idealized and NWP modeling work of QLCS tornadoes to study formation mechanisms in low CAPE/high shear environments. These studies can inform the project regarding needed observing systems and strategies.

PH3: ***What is the role of boundary layer mesoscale heterogeneity in modulating tornadic and non-tornadic environments in the Southeast?***
Source: Original Science Roadmap
Priority: High now that there has been a shift toward quasi-permanent fixed mesoscale network.

Recommended Timetable: Medium term given sufficient special V-SE observations could be collected in 2-3 years to begin to answer this question.
Comments: Antecedent work should involve priorities of assessing the character of PBL mesoscale heterogeneity under various flow and stability regimes, using a synergistic modeling/observing approach. This work can then inform observing strategies for this particular topic.

PH4: ***What is the role of the buoyancy profile, particularly for low-CAPE situations, in modulating storm behavior and tornadogenesis potential in the Southeast?***
Source: Physical processes working group, emerging from responses to question 4.
Priority: High, owing to poor physical understanding, poor forecast ability for low-CAPE events, and limited observations heretofore.
Recommended Timetable: Medium-to-long term
Related activities: Modeling studies from storm- to tornado-resolving scales of low-CAPE events; model PBL sensitivity studies and verification; high frequency surface upper-air observations (soundings, profilers)
Comments: Work should begin to define some of these buoyancy profile issues through heavily NWP-oriented approaches, perhaps validated against observed soundings obtained in risk-reduction activities, with an objective of defining required buoyancy profile observations.

PH5: ***How does the shape and magnitude of cold pools vary across the spectrum of tornadic and non-tornadic storms in the Southeast?***
Source: Original Science Roadmap
Priority: High, provided sufficient samples can be obtained via fixed mesoscale monitoring.
Recommended Timetable: Medium term
Related activities: Continuous monitoring of surface state over ~ 200 x 200 km domain, supplemented by episodic short-fuse sampling (surface state + disdrometer) to assess individual storm-scale variability. Eventual expansion of continuous mesoscale monitoring to quasi-permanent mode.
Comments: Analysis of existing FY16 and FY17 in situ (surface, disdrometer, profiler) datasets should be a priority for FY18. Ongoing data assimilation experiments will inform future strategies for optimal spatiotemporal sampling distribution. Methods should satisfy a number of priorities related to the identification of scales of bouyancy and wind shear in the southeast U.S.

A.5 Research Questions Related to NWP and Observations

In large part, these questions arise from the working group report in Appendix B.5.

MO1: ***What is the ability of current NWP models to simulate PBL processes, both in simple (fair weather, smooth terrain) and challenging (heterogeneities, terrain) conditions, and to predict rapid evolution of the storm environment?***

Source: The source of this question was the working group on the co-evolution of modeling and observations. This emerged as recommendation 1 in section 6.
Priority: High
Recommended timetable: 2018-2019
Related activities: Forecast verification, ESA, data-denial experiments, and physics-sensitivity experiments.
Comment: Included foci: model representation of low-level cloud characteristics, complex flows near terrain, terrain-related heterogeneity, and storm evolution near complex terrain.

MO2: ***Which parts of the atmospheric state must be better initialized (via data assimilation) in NWP models, and what are the implications for optimal observational strategies?***
Source: The source of this question was the working group on the co-evolution of modeling and observations. This is topic #2 in section 6 of the report.
Priority: High
Recommended timetable: 2018-2019
Related activities: OSSEs, ESA, and data-denial experiments.

MO3: ***Apart from the issue identified in MO2, what are the other leading sources of NWP model error in the Southeast?***
Source: The source of this question was the working group on the co-evolution of modeling and observations. This is topic #3 of Sec. 6 in the report.
Priority: Medium
Recommended timetable: 2019-2020
Related activities: Sensitivity experiments, e.g., grid spacing, initial condition resolution, physics schemes.
Comment: It may be best to focus first at larger scales, which are better observed and simulated, then proceed to smaller scales as our understanding and the quality of our datasets progress.

MO4: ***What are issues and problems in PBL closure in the "terra incognita" that must be addressed so that we can begin to trust models for their representations of processes important to tornado processes and prediction?***
Source: The source of this question was the working group on the co-evolution of modeling and observations. This is from topic #4 of Sec. 6 in the report.
Priority: High
Recommended timetable: Ongoing

MO5: ***What observations and microphysical parameterization improvements are needed to understand how microphysical processes in SE storms influence dynamics relevant to tornadogenesis?***

Source: The source of this question was the working group on the co-evolution of modeling and observations. This is from topic #4 of Sec. 6 in the report.
Priority: High
Recommended timetable: Short-to-medium term
Related activities: Comparing simulated to observed polarimetric variables and in situ (surface, balloon-borne, airborne) PSDs; model development via physics sensitivity experiments and comparisons with observations.
Comment: Short-term work should be aimed at clearly defining that more detailed observations that will be useful several years from now, in an activity such as the NCTS field program, with special attention to sensitivities in popular microphysics parameterizations and those most likely to be important in operational prediction in the short term.

A.6 Research Questions Related to Existing Observational Systems

In large part, these questions arise from the working group report in Appendix B.6.

LS1: ***What aspects of the physical processes and forcing (esp. downdrafts, mid-level precip formation) are associated with lightning trends in Southeast storms?***
Source: The source of this question was the working group on the use of existing operational data.

- Lightning trends have shown utility in detecting storm intensification
- This is an indirect indicator
- If processes were understood, we could improve the utility of the trend info
- GLM, unique LMA are available in VORTEX-SE

Priority: Will rise toward high priority as we gain confidence in observing systems, approaches, and strategies to give us confident estimates of vertical draft intensity.
Recommended timetable: Emphasize with the NCTS field program.

LS2: ***How do lightning characteristics in tornadic storms differ between the Southeast and other regions?***
Source: The source of this question was the working group on the use of existing operational data.

- Recommended that that comparisons of total lightning data from LMA, GLM, and other networks as available are made to quantify differences between regions (i.e.,. AL, West TX, Colorado, and Oklahoma).
- Provide practical applications of lightning data for forecasters in each region when diagnosing and interpreting storm intensification relative to other data sets (e.g., radar) for variable environments (e.g., low-CAPE, tropical).

Priority: Low-moderate
Recommended timetable: Ongoing
Comment: This topic is a good fit for research programs other than the NOAA VORTEX-SE grant program. As information from those programs, on this topic, becomes available, it will likely motivate more specific questions regarding the relationship between lightning and tornado occurrence in the Southeast.

Appendix B. Working Group Reports

This appendix simply repeats the working group reports for future reference and to provide context for the science plan agenda. Except for chairperson names, contributor's names have been removed.

B.1 Operational Forecasting Processes and Outcomes

2018 Update Comments:
All of the four overarching ideas and associated content that the working group developed in 2017 continue to be highly relevant in 2018. During the 2017 workshop and through subsequent discussions with working group members, an additional operationally-relevant research need emerged that pertains to overarching area #3 (Forecast and warning techniques, processes, and challenges):

- Forecasting and communicating the overlapping and co-occurrence of hazards -- Need to examine how forecasters conceptualize, identify, and detect overlapping and co-occurring severe weather hazards (e.g., tornadoes and flash floods, tornadoes within land-falling hurricanes), and how they negotiate the sociotechnical, ethical, and communication challenges of multiple hazards

Julie Demuth, NCAR, chair.

The following material is from the 2017 Science Plan Update:

To help inform discussions at the VORTEX-SE (VSE) 2016 workshop and the annual update to the VSE Science Plan, a working group was assembled to identify and synthesize key topics related to improving operational forecasting processes and outcomes.

The working group was asked to provide input about the most urgent operational issues that VSE research might help clarify and address; new approaches to weather hazard communication; and improvements in the collaboration between operations and VORTEX-SE research. These topics were discussed via a Google Drive document and one conference call. Several ideas emerged, and they are summarized here under four overarching areas. It should be noted that this document is far from comprehensive in breadth or depth of topics. Rather, we offer this as an interim step in the VSE planning process in the hopes that it will facilitate further contributions. Of note is that most research needs summarized here would benefit from close research collaborations among atmospheric science research, SBE research, and forecasters. Moreover, most research needs are relevant for tornadoes in the southeast but also in other regions of the US.

#1: Access, interpretation, and use of numerical weather prediction (NWP) guidance

Despite tremendous improvements in and the increasing ubiquity of NWP—particularly storm-scale, including ensemble-based, guidance—there are significant limitations in the access, interpretation, and use of this information by forecasters. These limitations, which can result in inefficient development and use of NWP, point to several research needs.

> *"Most forecasters are comfortable with making probabilistic forecasts of larger-scale phenomenon (snow accumulation, heavy rain, tropical cyclone) from a set of model forecasts. However, with something more complex like convection, you can't simply use the updraft helicity (or whatever) mean of 20 forecast members, when only 15 of them generate convection in your forecast area and 5 of them generate a decent supercell and none of those 5 are in the same location."*

· As this quote from a contributor of this working group illustrates, need to understand how and why forecasters do/don't use storm-scale guidance, especially from ensembles, for complex, mesoscale phenomena like convection. More specifically, these include the need to understand:

o What storm-scale (ensemble) information forecasters currently use and how, what information they need, and key operational problems, for example:

§ what model ingredients, parameters, and features (e.g., updraft helicity, tornado formation, tornado tracks, storm composite parameters) and what thresholds (e.g., updraft helicity > 45 m^2s^{-2}),

§ how forecasters interpret and use probabilistic, post-processed guidance from ensembles

o How forecasters combine and use different storm-scale guidance in their forecast process, including ingredients and feature-based guidance, and deterministic runs from ensembles coupled with probabilistic guidance

o How forecasters' interpretations, uses, and operational problems vary across different forecast time periods (0-3 hrs, 3-6 hours, 6+ hours, etc.) and scenarios (seasons, regimes, convective mode, etc.)

· Need to develop ways of verifying performance of storm-scale guidance and of understanding why the models do/don't perform well, including:

o How verification is conceptualized and measured differently and similarly by model developers versus forecasters, and how this shapes (and constrains) model improvement, use, etc.

o How forecasters subjectively "verify" model output in conjunction with available observations to assess its real-time utility

o How forecasters subjectively "verify" model skill post-event

o What objective verification of deterministic and probabilistic guidance forecasters currently use and what information is needed, including verification segmented by region and forecast scenarios (seasons, regime, convective mode, etc.)

o How to provide objective verification information (and training information as needed) in ways that are readily understandable by and accessible to forecasters to best meet their needs

· Overlapping but potentially also different from above, need to develop knowledge about how forecasters learn how to *understand* model information, including what is plausible but perhaps not obvious given a solution, and how they decide whether to *trust* and *adopt* new model information.

> *"The broader issue is we as forecasters are too often looking for [information and products] like these to streamline the forecast process and make sense of the ever increasing amount of data. Depending on a shift rotation and the pattern for that year, a forecaster could go several months at least between severe episodes. You then find yourself trying to remember where you found certain helpful ensembles from the last time you had a severe episode. Where was that paintball type image? Was it on the NCAR page or SPC?"*

· As this quote from a contributor of this working group illustrates, there is a need for well-organized, well-visualized, regularly updated repository of model information. This repository might include different models and the products available from them (and possibly information on latest model updates); objective verification information; and training. It might also be developed to be a "smart" repository, e.g., that does initial filtering of an event to diagnose key characteristics (e.g., storm mode) and then tailors the available model guidance accordingly.

#2: Forecast/warning decisions and communication, including of uncertainty, within NWS and with partners

With increasing and changing information (observations, model guidance, products, etc.) and practices comes questions about warning decision-making and communication of information about severe weather risks, both within NWS and with core NWS partners (e.g., public officials, media). These questions are particularly relevant given the weather community's intended and ongoing progression toward a paradigm of communicating uncertainty information (in more types of NWS products and other communication), including probabilistic information. There are several related research needs, some of which overlap with area #1 above.

· Need to understand how new guidance and tools factor into warning decisions and communication of risk information to key partners. Some examples include:

o How different uncertainty information, including probabilistic tools, factors into forecasters' risk assessment and warning decision making. These tools can include ensemble-based output (discussed above), statistical model-based tools such as ProbSevere (statistical model guidance developed by CIMSS that provides updates every few minutes), and other tools under development such as the Probabilistic Hazards Information (PHI) tool. More specifically are questions about:

§ How forecasters combine and use multiple tools

§ How forecasters use these different tools for different scenarios (e.g., high shear-low cape environments, nocturnal events

· Need to understand partners' needs and how forecasters communicate uncertainty with their key partners (and vice versa). Some examples include:

o When and how forecasters use different storm-scale ensemble guidance and/or other probabilistic tools (ProbSevere, PHI) to communicate with their partners (media, EMs, etc.)

o How forecasters convey uncertainty (both in the warning and outlook time scales) when dealing with frequent "conditional" environments (e.g., HSLC environments) in which there is

high end severe/tornado potential if a severe storm occurs, but with a low probability of an actual event

- Different partners' needs for what type of information, at what time, for what protective action purpose (and what is the range of those actions)
- How partners (e.g., EMs) might ascertain a non-event prior to their NWS partners, and how this gets negotiated

· Need to understand the different valences and meanings of "confidence", "probability", "certainty", and "uncertainty" as used by forecasters and their partners

- How do NWS partners and end-users understand probability relative to high-impact weather such as tornadoes? Is this interpreted differently or as effectively as confidence?
- What does confidence mean as an affective dimension of severe weather threats versus something like a range of possibilities, both in assessments of models but in communications with others (e.g. partners, schools, politicians, etc)?
- What do EMs mean when they ask for forecaster confidence? What do forecasters mean when they use this term individually or collectively? How does it differ from other kinds of confidence (e.g. confidence intervals, probabilistic information, trust, etc.)?
- How do uses / understandings of confidence change for different kinds of events or different temporal and spatial scales?
- When does a forecaster feel certain as evidenced by their taking action or making strong claims? What tools, experience, office procedures, and/or other factors come together to create certainty?
- How are forecasters "teaching" their partners about how to read uncertainty claims. Where are there misunderstandings? What does effective communication of uncertainty look like?

· Need to understand how goals of and communication within the NWS—among different national and local forecast offices—shape forecast and warning decisions and consistency of content (e.g., a unified image of severe weather versus differences of opinion about local nuances in meteorological phenomena (e.g., mode and timing)). Some examples include:

- How national center products shape and get shaped by local WFOs in determining tornado risk (mode, timing, severity, etc.)
- When and how local WFOs account for SPC information in their decisions about issuing pre-warning and warning communications
- How conversations that occur between local WFOs that share CWA boundaries shape decisions about issuing and communicating warning information
- How national products are translated for specific offices and localized threats and impacts at different lead-times (Day 1, 2, 3, etc.)
- For the above and beyond, how notions about—and increasing emphasis on— consistency mutually shape what kinds of warning information is conveyed, and what the pros and cons of this are

#3: Forecast and warning techniques, processes, and challenges

In addition to the NWP and communication challenges discussed above, other topics emerged related to forecast and warning techniques, processes, and challenges. This area was discussed in detail less compared to the other area, hence the first, overarching research need, but some specific topics emerged which follow:

· Need to understand what elements of the current warning system pose the biggest challenges for forecasters and how forecaster input is elicited to guide system changes

· Need a more complete understanding of boundary layer processes and evolution because this is critical to improving operational forecasts and warnings of severe weather. NWP struggles with accurate modeling of the PBL, and thus forecasts of crucial parameters and processes such as instability, low level shear, and convective initiation suffer. This is a general forecast problem, but it is even more critical in the Southeast for several reasons: the frequency of nocturnal tornadoes/severe weather and the need to understand PBL evolution at night; the evolution of the PBL in cool season events and near the interface with marine environments (e.g., how does the marine layer and bodies of water such as Lake Pontchartrain affect the PBL and severe weather in coastal LA/MS); and lack of knowledge about how terrain in the Southeast influences the evolution of the PBL

· Need for SPC tornado climatology, which has made tremendous strides and produced tangible benefits with 6-48 hour tornado forecasts, but more could be done to integrate this climatology into the 0-3 hour warning process

· (Overlaps with area #1 above) Challenge of data overload, especially with increasing storm-scale ensemble guidance, and thus need to understand forecasters' interpretations, uses, needs, and operational problems to better provide key model aspects (e.g., tendencies and reliability of models' handling of convective cold pools, surface dewpoints in strong warm advection, dewpoints over water, and so forth)

#4: Improved collaboration between operations and VORTEX-SE research

The working group also was asked to provide recommendations for improved collaboration between operations and VSE research. This topic was less discussed among the contributors, but a few ideas for consideration emerged. However, is it essential to respect that WFO management and forecasters have limited resources, and thus it may be worth eliciting from them what would be best ways to improve mutually beneficial collaboration with VSE.

· Encourage VSE researchers to collaborate with one or more WFOs as stakeholders, through quarterly or biannual conference calls to discuss planned research and findings

· Offer presentations of physical and social science findings to the Southeast WFOs, particularly those that have collaborated on VSE research. These presentations could be done virtually during the WFOs' annual severe weather meetings and at future VSE workshops

· Leverage the IOPs as focused opportunities for a conduit of information between operations and research

B.2 Working Group on Risk Perception and Communications

Mike Egnoto, Chair
(The text included here was extracted verbatim from the report of the working group, but has been reformatted.)

Introduction

This working group set out to assess how best to contribute to the future directions of the VORTEX-SE mission with the specific aim of improving Risk Perceptions and Communication. The findings discussed here present an overall view of social science, assessments of the projects funded in 2015 and 2016, and evaluates several knowledge gaps covering specific areas of research, methodological limitations, and programmatic limitations which were uncovered. Phase one of this report was developed via an in-depth qualitative review of funded projects on the VORTEX-SE shared drive. Special attention was paid to outcomes, methodologies, and points of interest. Phase two of this report evaluates the cost of conducting social scientific research. Additionally, group email threads of frustrations and approaches were used to solicit group opinion throughout the process.

Brief Review of Risk Communication

At the most fundamental level, risk communication evaluates the exchange of information before, during, and after crises. VORTEX-SE projects largely focused on information exchanges before and during crises, attending specifically to how information impacts the decision-making process of individuals and whether they are aware of, and choose to adhere to, emergency directives to help lower their risk during critical weather incidents. There were additional underlying assumptions that previous experience, in the form of past disaster contact, may inform current decision making, across several projects. Simplistically, the process of adherence to emergency directives can be thought of as a five-step model where individuals must: 1) Determine the problem, 2) List alternative solutions, 3) Choose a solution, 4) Implement that solution, 5) Evaluate the outcomes of that decision (FEMA, 2014). Poignantly, all phases are not necessary to engage with risk communication. Information recipients, if unaware of the scope of the problem, never fully evaluate possible solutions, or even if aware, may be unable of determining the total breadth of solutions available to them. Further compounding this frustration, is the potential for a lack of ability to carry out the solution chosen, and the alarming opportunity for repeated failures due to a lack of reflection. Collectively, these issues can look like complacency whereby individuals, either due to lack of information, problem solving, or insufficient stockpile of resources and capabilities, cannot engage effectively with emergency directives. This complicates much of the VORTEX-SE goal of understanding why complacency exists – but does provide meaningful points of investigation.

VORTEX-SE Focal Points

Within the 2015-2016 funding cycle, significant emphasis within the social scientific projects focused on understanding the role of complacency (Ellis et al; Egnoto et al). Largely, these investigations looked at risk perceptions, warning access, environmental constraints to information and shelter, and foundational knowledge of tornadoes with the goal of determining base-levels of complacency that could be expected across the Southeastern US and create resources to mitigate these complications. Thinking back to the above phases of risk communication – **the 2015-2016 VORTEX-SE social science funding cycle focused largely on how problems are determined, and how possible solutions are evaluated**.

The 2016-2017 funding cycle emphasizes communication sources (LaDue et al), evolving understandings of risk as it interacts with increasing knowledge(Demuth et al), and individual/environmental influences to risk internalization (Broomell et al). Largely, these works seem to have refined previous areas of investigation or spread into novel new domains. **Specifically, the 2016-2017 cycle expands more directly into how solutions are chosen and implemented, while also improving 2015-2016.** Thus, two conclusions become apparent. First, future VORTEX-SE work should consider in the short-term how and if individuals:

1- *Reflect on the outcomes of previous emergency weather decisions, and how that reflection impacts future decision processes, and for how long*

A number of investigations previously funded by VORTEX-SE have some acknowledgement of prior experience, a more robust understanding is worthy of future investigations. Importantly, VORTEX-SE should seek to understand not just how past experiences and outcomes from previous decisions impact future weather events, but:

2- *How members who make decisions are influenced by their own experience and others in their care*

VORTEX-SE projects seem to largely focus on how communities can be improved by risk and crisis communication from aggregating individual responses to community-level behaviors. Yet, findings from previous VORTEX-SE Research notes that many respondents are caregivers for various family members, pets, and others. Risks may be taken on the individual level in the hope of improving the safety of others that are in care-receiving positions. Therefore a major take-away from this investigation becomes apparent:

Major Theme One: Is complacency an individual or group level trait, and can complacency be mitigated through the experiences of decision-makers or decision-followers within these groups?

This conceptualization logically extends into a third conclusion, which describes how to leverage the above relationship if it does exist for group benefit. Thus:

3- *How can post-crisis information be spread to leverage relevant narratives of care-givers and care-receivers to improve compliance with future emergency weather information*

Between 2015-2016, and 2016-2017, Resilience was mentioned in 1/3 of all projects. Resilience is a growing field of research with a platitude of definitions in existence, but most revolve around a central theme of rebuilding after a disaster to a stronger level than before, or decreasing the impact of a disaster before it occurs. Resiliency research, by focusing on decreasing the impact of disasters, has a logical link to reducing complacency as a means of achieving this end as complacency focuses on the rate of engagement by various publics with risk-reducing activities. As such, it may be worthwhile integrating a broader them of resilience in future VORTEX-SE calls. Thus:

Major Theme Two: VORTEX-SE should evaluate if a more holistic resiliency framework should be applied over an emphasis on complacency within social science focused research

Both major themes focus on the idea that the way information is communicated, either when combined with past experiences or presented in such a way as to encourage behaviors that involve relevant others – operate on the assumption that the content of information presented can change. However, as the content and structure of how emergency alerts and WEAs are regulated by the FCC, and these messages are heavily templatized, a significant roadblock within VORTEX-SE cannot be ignored. **If the structure and content of the messages cannot be changed as dispersed by NOAA, VORTEX-SE needs to identify partners (like local meteorologists) and provide guidance and findings on how to share information efficaciously through their channels.** It seems some work in the current VORTEX-SE funding cycle by LaDue and colleagues is beginning this work – but it may be advisable to make this a heavier focus of the program at large. Therefore, it is suggested:

Major Theme Three: VORTEX-SE needs to identify a way of translating much of its communication findings to partners who can enact the changes in communication dispersed during tornadoes

Costs of Social Science

A common frustration from a number of social science researchers during the second call of VORTEX-SE funding was the restructuring of the budget cap for social science research. A significant goal of this research was to assess what impact, if any, that restructuring may have for the long-term productivity of the VORTEX-SE program. Access to previous budgets and workplans is somewhat limited, but the team was able to pull together a collection of 11 one-year awards from various U.S. government agencies focused on social science research from the University at Maryland (only institution where full awards could be accessed) and estimate the costs for various projects with differing levels of scope. As was pointed out by several collaborators on this report, social science often relies on multi-method triangulation. By that, they often do several methods (surveys, focus groups, interviews, ethnographies, etc.) as a means of improving confidence in findings. As such, the frequency and extent of multi-method approaches was also evaluated.

Of the 11 awards evaluated, total costs ranged from $112,142.22 to $470,595.50 (M = $241,688.28, SD = $35,430.92). On average, salary for key personnel accounted for 31% of the total budget, with salaries for supplemental personnel (research assistants, graduate students, etc.) accounting for another 22%. A total of 40% of the budget was allocated directly to research expenses (data collection mainly), but this varied more than most groups, ranging from 11% to over 60%. Cost of personnel (usually supplemental) generally seemed to vary in direct opposition to cost of data collection. This is likely due to budgetary caps and how open-source data can be utilized. The remainder of grants is accounted for by facilities, outside consultants, sub-awards (if applicable) supplies, and fringe benefits. When looking at the dollar-amount averages, the mean salary for key personnel was $73,391, whereas the average cost of research/data collection was $96,675.31. Most of the research evaluated used 4 methodological points (range 3-7). Most commonly, it was: Literature review, Focus Group, Survey 1, Survey 2. Fewer method points removed either a confirmatory survey (survey 2) or the focus groups. Larger studies included more robust development and validation checks. Several conclusions can be drawn from the above, first:

Major Theme Four: NOAA's budgetary cap of $150,000 will likely change the scope of social science projects that can be conducted

The reduced funding amount is not insurmountable, as other awards seem to have lower caps (recall the lowest award was $112,142.22 annually). However, those projects have fewer personnel, fewer methodological approaches, and are narrower in scope. It is likely appropriate to targeted very focused questions NOAA would like answered, and have an institutionalized mechanism of consolidating findings across these more abbreviated investigations.

One approach where NOAA may be able to capitalize on the new budget cap is by integrating newer faculty with less/no funding history. As key personnel costs are largely fixed, one can either reduce the cost of data collection, or lower the personnel themselves by targeting earlier career applicants. Thus:

1- *Key personnel costs are largely fixed, so cost savings are most likely to be realized through:*
    Reduction in data collection methodologies
    Funding of more junior investigators which may have lower costs

A final consideration, is some institutions may be priced out of competitiveness for VORTEX-SE Funding. With many universities having overhead costs cresting 50% of total award amounts, VORTEX-SE may have to target single personnel or small research teams on focused, likely geographically local, areas of investigation. Notably, none of these issues are insurmountable, fatal, or otherwise apocalyptic. They do however, indicate benefit in considering *how* to structure future social science projects to capitalize on the $150,000 cap. There does seem to be slight indication for a more natural break point around $190,000 where NOAA may maintain projects of a larger scope, but with the amount of data analyzed, the authors are not confident in that finding.

Conclusions

Overall, 4 major themes with several sub-themes were uncovered.

Major Theme One: Is complacency an individual or group level trait, and can complacency be mitigated through the experiences of decision-makers or decision-followers within these groups?

1- *Reflect on the outcomes of previous emergency weather decisions, and how that reflection impacts future decision processes, and for how long*
2- *How members who make decisions are influenced by their own experience and others in their care*
3- *How can post-crisis information be spread to leverage relevant narratives of care-givers and care-receivers to improve compliance with future emergency weather information*

Major Theme Two: VORTEX-SE should evaluate if a more holistic resiliency framework should be applied over an emphasis on complacency within social science focused research

Major Theme Three: VORTEX-SE needs to identify a way of translating much of its communication findings to partners who can enact the changes in communication dispersed during tornadoes

Major Theme Four: NOAA's budgetary cap of $150,000 will likely change the scope of social science projects that can be conducted

1- Key personnel costs are largely fixed, so cost savings are most likely to be realized through:

Reduction in data collection methodologies
Funding of more junior investigators which may have lower costs

Half of the take-aways are readily addressable in the research itself conducted by VORTEX-SE, but points 3 and 4 indicate more fundamental operating procedures of NOAA and Government Agencies. Likely, immediate adjustment in these areas is not only impractical, but is also largely impossible. Theme 3 seems to have the ability to be addressed from a research perspective to some extent (as indicated by current work by LaDue and colleagues), but an underlying restriction on how NOAA can communicate still exists. Theme 4 will likely come as no surprise to anyone evaluating this report, but did bear mention and significant investigation.

B.3 Working Group on Societal Vulnerability and Refining the Understanding of the Southeast Tornado Problem

(Kim Klockow and Walker Ashley, co-chairs)

2018 Update Comments:

(No significant changes were required from the 2017 update.)

The following material is from the 2017 Science Plan Update:

As part of an annual update to the Vortex-Southeast (Vortex-SE) Science Plan, the Science Steering Committee established a working group to clarify vulnerability issues in the Southeast region, including a clearer articulation of what is known about these problems and where key gaps exist. Specifically, this working group was motivated by the following three prompts:

1. Do we have, or can we produce, killer tornado statistics specifically for the Southeast?

2. Do we have, or can we produce, a data set that gives storm types, casualties, warning lead times, POD, housing and landscape characteristics, shelter availability, causes of death, etc. specifically for SE US tornadoes? Would synthesizing findings from this type of data set help us define the issues that require the most attention?

3. How should the text in the Science Roadmap on "Understanding and reducing societal vulnerability to tornadoes" be revised to clarify a) what is known and what are the key knowledge gaps; b) what the initial priority research topics and methods to address these gaps; and c) how the knowledge gained from this work can be used to help articulate VORTEX-SE physical science and operational priorities?

To address these prompts, the working group solicited input from numerous social and physical scientists whose work relates most closely: those who work in operations within the NWS, interdisciplinary scholars working to understand trends in exposure that contribute to tornado vulnerability, and social scientists studying the effects of warning practices on populations in the southeast as compared to other regions. In phone and email conversations, several topics emerged as critical for framing the questions themselves, and for offering the insight requested.

The working group recommends that a final exposition on Southeast tornado vulnerability include each of the following topics and identified gaps in observations, perspectives, and knowledge. As the topics each expound on a small part of the vulnerability puzzle, overlaps in both known issues and research gaps occur throughout the document.

Defining the "Southeast" for VORTEX-SE purposes

It is natural for those that have an interest in the VORTEX-SE project to ponder what is considered the "Southeast" – indeed, this question lies at the heart of defining the successes that could come from Vortex-SE; for whom is this research intended to be beneficial? Delineating geographical boundaries, not unlike any classification system in science, can be difficult. While it may be rather simple to employ political (e.g., state) or physiographic boundaries (e.g., biogeographic, such as

dominant forest type, or hydrologic, such as the Mississippi or Ohio Rivers), etc.) to define a region, at least in this case, it may be more appropriate to examine the geography of tornado impacts and their underlying causes to demarcate the region of study and where to focus project efforts. After all, tornadoes routinely cross geographic and physiographic boundaries and the primary goal of the project is to reduce tornado impacts.

Perhaps the most vivid and recognized impact of tornadoes are the fatalities they can engender. The long-term distribution of fatalities and the killer tornadoes that produce them can be used to illuminate the region that has the greatest overlap of underlying physical and social vulnerabilities with a high risk of the hazard itself. Figure 1 reveals that, if using killer tornadoes as a marker, the greatest threat to society is in the southeast quarter of the conterminous U.S., in a region generally east of Interstate-35, southeast of Interstate-44, and south of Interstate-64.

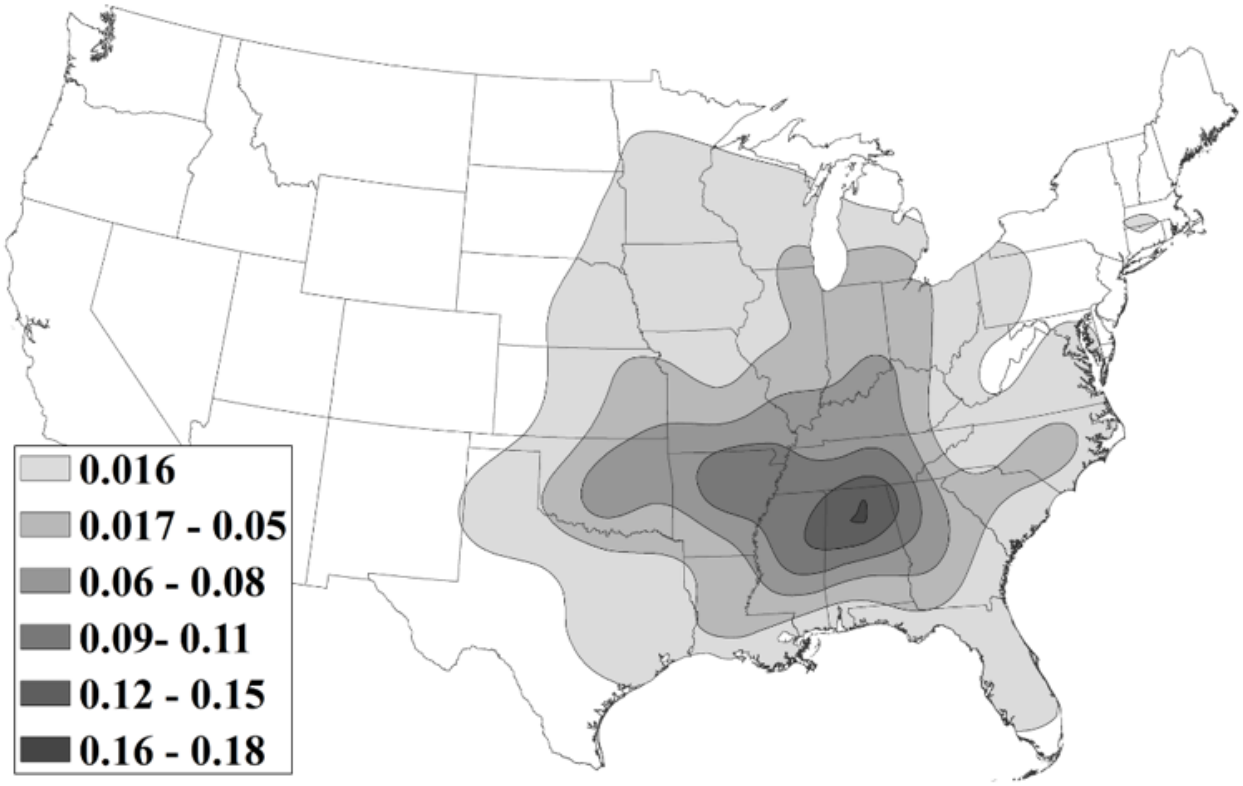

Figure 1. *The number of mean annual killer EF1+ tornado paths from 1954 to 2014 across the conterminous U.S. Path grid intersect counts are calculated on an 80 km × 80 km grid from 1954 to 2014 and smoothed using a 3 × 3 low-pass filter (after Ashley and Strader 2016).*

This "Southeast" region includes areas of eastern Texas and Oklahoma, southern Missouri, Arkansas, Louisiana, southern Kentucky, Tennessee, Mississippi, Alabama, Georgia, South and North Carolina, southern Virginia, as well as portions of northern Florida. The greatest threat to life is clustered in the Mid-South, which includes Alabama, Arkansas, Georgia, Mississippi and Tennessee. The working group recommends that the Vortex-SE Science Steering Committee strongly consider a working definition of the Southeast that is based on this impact and need, with a heightened focus on the Mid-South region.

What is known, and remains unknown, in the production of killer tornado statistics for the Southeast

The disproportionately large tornado mortality and killer tornado rates found in the Southeast compared to other at-risk regions in the U.S. are a defining characteristic of the tornado problem that has plagued the region (Fig. 1). For instance, recent research has illustrated that the mortality rate for the Southeast is 4 to 5 times greater than that found in the conterminous U.S. (Fig. 2). By assessing contemporary tornado mortality rates and their spatial characteristics, research has begun to explore how the complex tapestry of physical and social vulnerabilities at the regional scale commingles with a very high climatological risk of significant tornadoes to produce the unique tornado impacts found in the SE. While much is understood about the regional perspective of tornado fatalities, injuries, and even the climatological characteristics of the hazard itself, less is known about how these factors influence mortality and morbidity at the local scale. For instance, regional vulnerability assessments have traditionally used data gathered from decennial censuses; these data are beleaguered by stationarity, changing spatial enumerations, and may not contain the granularity necessary to discover what specific factors are responsible for amplifying or attenuating tornado impacts. Both qualitative and quantitative research at the fine-scale of the tornado hazard are required to remedy this data, and affiliated knowledge, deficiency.

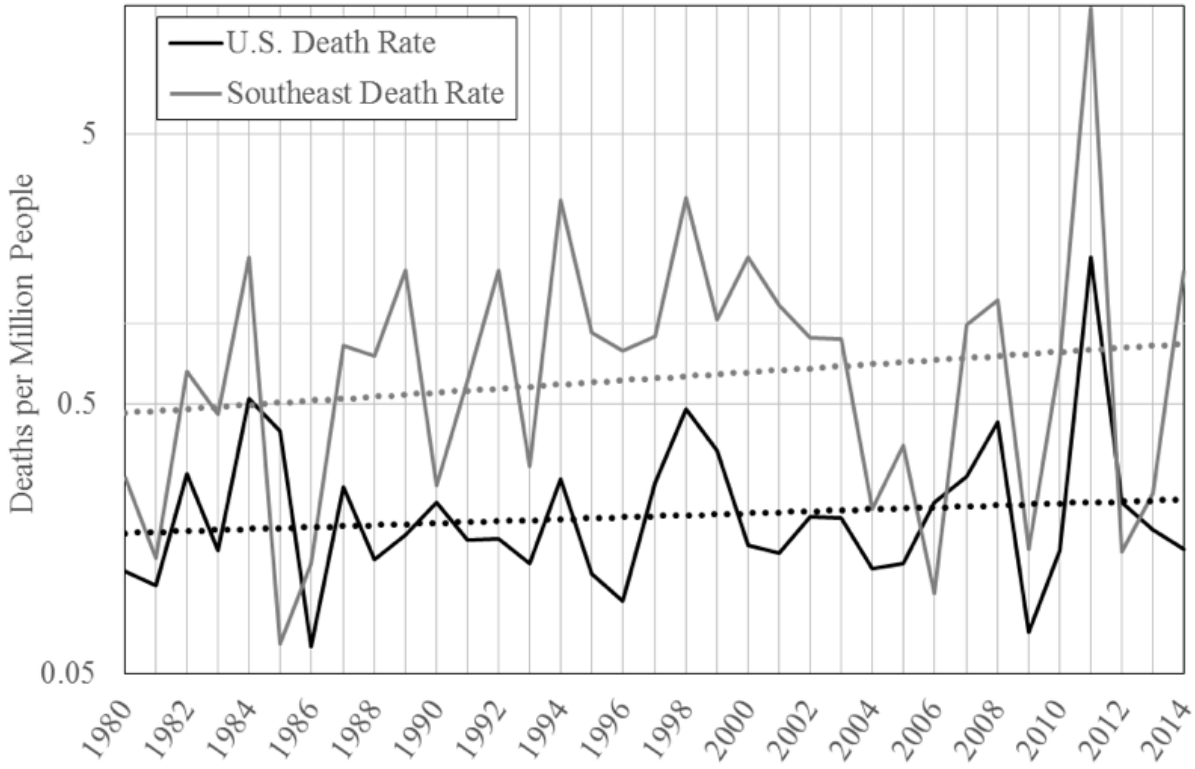

Figure 2. *Tornado death rate per million people per year in the conterminous U.S. (black) and SE (gray) from 1980 to 2014. The solid lines represent the raw tornado death rates, while the dashed lines are linear least squares fits to the death rates (after Ashley and Strader 2016).*

We have a very limited understanding of survivability in tornadoes and how proactive mitigation steps for those in the tornado path lead to reduced vulnerabilities and, ultimately, death and injury rates – a point we return to in the vulnerability and adaptive capacity section. Uncovering these tornado "successes" is required, as it is likely more effective to build on salient mitigation activities that increase survivability, rather than focus solely on factors that enhance mortality.

To discover these factors, post-event assessments of rates of survivability, as well as qualitative research pinpointing successful mitigation, is essential to achieving the goals of the project. In addition, recent research has illustrated that the relatively high population and housing density of the Southeast leads to elevated rates of exposure to the tornado hazard compared to other at-risk regions such as the Great Plains and Midwest. How does sprawl and unencumbered development—hallmarks of many locations in the Southeast—intermingle with relatively lax building code and affiliated enforcement to amplify mortality, morbidity, and damage rates? Much of this policy is locally driven and not well understood. Correspondingly, mobile homes, as well as other weak-frame housing stock, present a significant hurdle to reducing mortality rates in the Southeast. Nearly half of all tornado fatalities occur in mobile homes and, because the Southeast has a very high, and growing, proportion of this extremely vulnerable housing stock, understanding the proliferation of this housing while focusing on shelter needs, their placement, and other mitigation activities for mobile home residents is required if the project's primary goal of reducing mortality in the region is to be attained.

A recent meta-analysis of a large dataset including variables such as convective mode, environmental parameters, and radar attributes found that not only do discrete right-moving supercells account for tornadic storm modes in the Southeast, but also other modes: cell in cluster, cell in line, and QLCS, with cell-in- line and QLCS modes predominating east-of-Mississippi River tornadoes. In the wintertime, both QLCS and right-moving supercell modes are seen commonly in the Southeast, at a time when tornadic storms are uncommon elsewhere.

With the cold-season component linked to a general dynamical forcing for convection, diurnal versus nocturnal influences have less of an effect on convection than that driven more by surface heating. So, wintertime events can last well into the night.

In general, the challenges of warning for linear/cluster-mode convection with interacting updrafts and fast-evolving convective elements influenced by small-scale subtleties/boundary interactions yield a tremendous challenge in keeping POD up, reducing FAR, and gaining considerable lead time – all simultaneously. Should we be concerned about warning every weak QLCS tornado for the sake of maximizing POD when we know FAR goes up? This is a challenging question for both the SBE and physical sciences.

Ultimately, the intricacies of convective interactions and their relationships to the background kinematic and thermodynamic environment should play a significant role in warning decision-

making. Yet, inadequacies in the spatiotemporal frequency of sampling the real atmosphere must be resolved before we can make better short-term predictions relevant for improving the accuracy and timeliness of convective warnings. Not only would higher-frequency sampling of the atmosphere be relevant, but also improvements to numerical simulations – and, in particular, to the parameterization schemes used to represent physical processes – would be necessary. Parameterizing the planetary boundary layer is crucial to better simulating these environments, directly relevant to the Warn-on- Forecast/FACETs perspective. This highlights the necessity for an emphasis on the physical science understanding to encourage
improvements to the warning program. The need for a more robust set of observations ties directly into the physical-science side of warning improvements, as well.

Connecting Convective Mode and Storm Timing to Fatalities

A limited amount of work has assessed the climatology of fatal tornadic events by storm type. An effort by Schoen and Ashley (2011) revealed that nearly 90% of tornado deaths occur in isolated supercells (78%) or supercells embedded within an organized convective line (12%), with most of these events occurring in the SE. With the recent rollout of dual pol radar, additional research should investigate the storm characteristics of fatal tornadic events; those findings should be intersected with results provided by parallel SBE research to reveal any socio-environment interactions that may be occurring in these events.

A tornado occurring late at night (between midnight and 6am) causes significantly more injuries and fatalities compared to one occurring at other times of day. Nocturnal tornadoes are 2.5 times more likely to be fatal than daytime tornadoes and the proportion of fatalities from nocturnal tornadoes continues to rise. This is an issue in the Southeast where tornadoes are common during the cool season when daylight is at a minimum, resulting in one third to nearly one half of tornadoes in southern states occurring at night.

Nocturnal tornadoes are particularly threatening because they occur in decreased visibility and when most people have a tendency to be asleep. They are also more likely to go unwarned than daytime tornadoes. Another consideration is the type of structure a person is in, which changes over the course of a day, from reinforced schools and workplaces during the day, to weaker buildings such as mobile and single-family homes at night (Simmons and Sutter 2005) where tornado fatalities are more common. Nocturnal tornadoes are responsible for nearly two-thirds of the tornado fatalities in mobile homes. No published studies to date have assessed human behavior during nocturnal events. Such social science-oriented studies could provide information to help improve warning systems and potentially decrease fatality rates from these events.

Connecting Lead Time and Casualties

Tornadoes in the Southeast have a mean warning lead time about one minute less than the rest of the nation, and a higher local FAR in recent years, although the differences are not statistically

significant in aggregate. Analysis of the effect of warnings on fatalities nationally shows that warnings reduce fatalities and injuries generally, while a higher FAR increases fatalities and injuries. The impact of warnings may differ in the SE, however, compared with the rest of the nation. Regression analysis of Southeast tornadoes only indicates that a higher FAR reduces fatalities, the opposite of the relationship for the rest of the nation. And lead times in excess of 20 minutes have a much greater effect in reducing fatalities in the Southeast than in the rest of the nation.

The analysis above is based on tornadoes over the years from 1987 to 2006, but the number of killer tornadoes in the Southeast is relatively small over that period of time. One open research question is whether the impact of warnings on fatalities has changed since the switch to storm-based warnings in 2007.

An assessment of fatality and warning data from 1986 through 2007 indicated that 23.7% of tornado fatalities were unwarned for the conterminous U.S.; however, most these unwarned tornado fatalities occurred prior to the mid-1990s, which coincided with the NWS modernization. The number of unwarned tornado fatalities in the Southeast is comparable compared to other parts of the U.S. Though unwarned fatal tornadic events account for a very low percentage of events, additional research is required to understand the when, why, and how these cases can still occur in the modern era.

Connecting Warning Performance to Behavior

Empirical research on the influence of warning system performance on public responses to tornado warnings is inconclusive and incomplete. Research is inconclusive because some studies indicate that recurrent false alarms reduce public confidence in warning systems; others indicate that there is no relationship between false alarms and confidence; and a few studies suggest that false alarms may increase (rather than decrease) confidence in warning systems. Nevertheless, there is a compelling correlation between false alarm rates and tornado impacts.

On average, tornado-related deaths and injuries are higher in regions that experience more false alarms than the rest of the country. The “false alarm effect” might explain this correlation, but more research is necessary to assess causality. Do recurrent false alarms cause tornado-related deaths/injuries, or is the correlation produced by a confounding factor (or set of factors) that causes both false alarms and tornado-related deaths/injuries (e.g., nocturnal tornadoes)?

Research is incomplete for two reasons. First, researchers typically focus on false alarms alone, rather than false alarms, missed events (probability of detection), and lead-time, all of which impact warning system performance and, possibly, public confidence in warning systems.

Second, we know relatively little about the social and psychological mechanisms that connect warning system performance to individual and collective responses to warnings. In recent years, scientists have started to fill these gaps. Early findings indicate that missed events are as

important (if not more important) than false alarms in shaping the public responses to tornado warnings. This research also suggests that public perceptions about warning system performance systematically influence public trust in warning systems and, consequently, public responses to tornado warnings. The study that produced this finding indicates that actual performance is but one of the many factors that may influence subjective perceptions about performance. A subsequent study (on false alarms alone) found that there is no relationship between perceptions and reality. Either way, more research is necessary to identify the factors that influence perceptions about warning system performance. Differences aside, there appears to be a positive relationship between perceptions about warning system performance (FAR and POD), trust in warning systems, and warning responsiveness. Among other things, we need to know 1) if lead-time influences perceptions about warning system accuracy; 2) if geographic differences or "weather cultures" influence perceptions about warning system accuracy; and 3) what (if anything) forecast offices can do to influence public perceptions about warning system accuracy.

From Vulnerability to Adaptive Capacity

Vulnerability arises from exposure and sensitivity to impacts, and limitations to the capacity to adapt or cope with the impacts. While certain sociodemographic, housing, or other characteristics can indicate potential for harm, they do not necessarily indicate that a person or population is more "vulnerable". People are not vulnerable because of their characteristics, but because of limited access to resources (including information) due to the complex social relationships that can be (but are not always) associated with certain characteristics. Thus, it is important to recognize that although population, housing, and other characteristics are proxies for the potential to suffer harm, we need to better understand why people actually suffer harm in specific contexts in order to address vulnerabilities to tornado threats in the SE.

Also important are the capacities that people have that help them to cope with anticipated or actual impacts. Populations that are considered "vulnerable" often have adaptive capacities, such as social networks, cultural practices, and local knowledge that help them reduce harm when a hazard such as a tornado threatens. In the Southeast region, research on the role of social networks to transmit severe weather forecast, warning, and protective behavior information should be a priority. Different populations should also be studied to identify other adaptive capacities and understand how and when they can help empower people to make protective decisions.

B.4 Working Group Involving Observing Atmospheric Processes or Historical Data

(Dan Dawson, Mike Coniglio, co-chairs)

2018 Update Comments:

The following material was generated by SPC representatives on the SSC on 9 Feb 2018:

1. Recommend more effective observational sampling of pre-storm and near-storm environments covering a large geographic domain to better document synoptic and mesoscale environment evolution. We should step back and better understand the broader scales that "frame" smaller mesoscale/stormscale response before focusing only on a limited number of very small-area intensive observational periods. Better sampling of the HSLC part of the parameter space would likely provide better avenues from research in the longer term (after Meso18-19)

2. Recommend collecting observational data over considerably larger time/space domain, owing to persistent, longer term but lower frequency of cool season tornado days compared to Central US. This is more consistent with:
- Geographic area of states defined as "Southeast"
- Seasonal extent of cool season HSLC environment hours during November-March

3. Thus, a longer, continuous observational sampling network is needed to better assess the cool season background environment, how it evolves leading into and during tornado episodes, as well as similar appearing null cases.
- Synoptic scale features remain important in controlling the return flow cycle and attendant air mass character within the evolving warm sector.
- Key forecasting challenges include HSLC environments, such as within marginally buoyant warm sectors and near the northern extent of inland, more buoyant warm sectors where low-level shear/SRH are enhanced along/just north of surface warm front.

4. Supplement the longer-term continuous observing network with higher frequency of fixed location NWS RAOB launches starting ~2 days prior to a possible severe episode, similar to enhancements to RAOB frequency for tropical cyclones approaching the US.
    - Start 6-h RAOBs ~ 2 days in advance
    - Increase to 3-h RAOBs within/near warm sector during Day 1.
- Consider supplementing NWS RAOBs with university partner fixed location RAOBs at TAMU, ULM, MSU, and UAH (gap-filler soundings).
- These additional soundings will support OSSE/data denial experiments to assess impacts of additional soundings on model performance, and NWS forecaster evaluation of data utility on short-term forecasting/warning decision-making by NWS forecasters.

5. Uncertainty can be larger in predicting details and evolution of convective mode (discrete persistent supercells, QLCS, less organized bands/clusters) within in strongly forced situations associated with fast-moving baroclinic systems.
- Capping is typically limited and a multitude of storms (not necessarily severe) can be ongoing for longer periods of time.
- Progression from CI to SI (severe initiation) can be is quite variable in time within HSLC environments.
- Real-time estimates of CAPE magnitude in time/space from diagnostic and forecast perspectives are likely subject to larger percentage errors, and how much CAPE is "enough" to support tornadic supercells is unknown.

6. When possible, further supplement potential tornado events on Day 1 with targeted higher resolution observing systems (fixed and mobile) for a few cases.

The following material is from the 2017 Science Plan Update:

1. What are the current low-hanging fruit that can have the nearest-term impact on NWS performance in tornado forecasting and warning?

EDITORIAL SUMMARY: The avenues of pursuit most likely to provide the biggest impact on the near term can be broadly summarized into the following categories:

1. Changes in warning/verification policy on the part of the NWS, along with better forecaster training. Although the trend in recent years is for smaller warnings, there's a perception that tornado warnings are often too large. The NWS should perhaps put limits on the space and time scales for warnings. Large warnings may be issued for two reasons, 1) owing to how NWS verifies warnings (casting a large net increases the chances of a hit and reduces the 'fear factor' of the forecaster) and 2) to avoid confusing the public. But large warnings may also be a consequence of workload issues (reducing the need to issue multiple warnings for one storm). In other cases, warnings may be issued that seem to betray a lack of understanding of storm structure and behavior. In the former cases, revising warning policy to deemphasize simplistic "hit or miss the polygon" metrics and instead encourage a more targeted approach is recommended. A metric that measures accuracy and false alarms spatially and temporally should be computed and communicated in real time, at least internally. Furthermore, better and more consistent forecaster training on current scientific understanding of severe storm behavior is warranted. A study of forecaster "philosophies" across the NWS (this may already be ongoing) may help explain recent trends in warning performance and offer clues to a way forward. This type of research should be used to determine, for example, if tags allowed for tornado warnings should be expanded beyond "OBSERVED" and "RADAR INDICATED" to include "POSSIBLE", since informal surveys of warning forecasters indicate they warn when their confidence reaches ~30%.
2. Better public education of the current level of understanding of the science of tornadoes and severe storms, as well as both the strengths and the limits of our capability to detect and warn for these phenomena.
3. Adding additional WSR-88D radars, or CASA-like radars, to fill in gaps in low-level coverage, which is particularly problematic in parts of AR, MS, LA, and AL. While expensive, this would provide immediate and proven benefits to tornado detection. Identifying the utility, need, spacing, etc. will likely be an outcome of VSE research.
4. Coordinated scientific verification of new and emerging research and forecasting tools and techniques to better inform forecasters. Examples include assessing the impact on tornado warning performance of SAILS/MESO-SAILS scanning techniques, polarimetric observations, and emerging Warn-on-Forecast-style data assimilation and short-range convective modeling systems.
5. Data mining of existing and emerging databases that integrate severe weather reports and associated multi-sensor environmental data, to provide enhanced probabilistic forecasts of tornadoes and other severe hazards.

2. Evaluate the assertion that supercell in-situ observations in the Southeast will be so infrequent, and of such short duration, that process studies will likely yield little/no new knowledge over the course of the next decade or so. Put another way, how many years of in-situ observing will be required to obtain one process study case of similar quality to some of the VORTEX2 cases?

EDITORIAL SUMMARY: The consensus of the working group is that obtaining a dataset of a quality comparable to that obtained during VORTEX2 is very unlikely on a timescale of several years with the current funding model and the logistical constraints imposed on field work. By dataset quality, we're referring to the completeness of datasets during a significant portion of a storm's life cycle and a wide variety of data types (a caveat is that VORTEX-SE would offer much more complete information on mesoscale external influences using profiling systems). The primarily logistical constraint is the very unfavorable geography of the VORTEX-SE domain, but the infrequency of events, and their lack of predictability more than 2-3 days ahead of time (the lead time typically required for personnel to travel and prepare for the IOP), also presents significant practical challenges for participants.

3. Given the information developed in #2, consider all observing approaches for feasibility and likelihood to yield new knowledge. Consider fixed continuous remote sensing, fixed/deployed in situ sensing, ad hoc deployed networks (e.g. the radar networks in Spring 2016), targeted in situ sensors, and any/all others you can think of.

EDITORIAL SUMMARY: A fresh approach to data collection beyond that used in previous VORTEX projects is strongly recommended by the working group. Campaign strategies specifically tailored to the aforementioned geographic challenges, particularly those emphasizing long-duration high-spatiotemporal-resolution fixed site observation networks (particularly surface stations and profilers, but also disdrometers, lightning networks, rawinsondes, and appropriately sited radars) have strong potential to yield substantial new knowledge of tornado-related processes. This is especially true of those processes operating on the meso-gamma and meso-beta scales such as storm interactions and the modification of the near-storm meso-beta-scale environment, as well as those tied to terrain inhomogeneities. It's plausible that storm interactions may be relatively more important for typical VORTEX-SE tornadic environments, owing to weaker CIN than their Plains counterparts, and observation strategies designed for this state of affairs may yield much fruit. Such a strategy would statistically all but ensure quality observations of low-probability "oddball" tornado cases that are the most challenging for scientific understanding, let alone prediction. However, such a strategy may necessitate a change in the current funding structure of VORTEX-SE. Furthermore, a "hybrid approach" whereby a larger-scale fixed observation network is augmented by nimble opportunistic, targeted small-scale "micronets", involving surface-observing systems (e.g. mobile mesonets), ground-based profilers, mobile radars, UAVs, and airborne radar observations, appears feasible and such an approach has already shown promise in the 2016 VORTEX-SE field campaign. <u>An important final note is that</u>

extensive pre-experiment scouting of sites will be essential if the siting for the mobile radars is to be flexible during the IOP.

4. What research can/should be done about cold season tornadoes (Nov-Feb)?

EDITORIAL SUMMARY: Cold season tornado environments in the SE-US are challenging on a number of levels, not the least of which is their relative rarity. As such, much the same considerations as above apply here, and a quasi-permanent multi-sensor network would likely be required to yield substantial new knowledge on the observation front. In the meantime, there is potential for advancement in this area through climatological studies using existing databases and modeling studies. The latter should be designed to assess the sensitivity of cool season tornado environments to various model physical parameterizations, particularly boundary layer, surface, and microphysics schemes. This approach is motivated in part by the need for a better assessment of the role of environmental CAPE/buoyancy profiles, particularly in low-CAPE cold-season tornadic environments, as such are poorly observed and/or simulated by current observation networks and NWP guidance. It's also not clear how cold-season tornadic storms and associated tornadoes differ dynamically or otherwise from their more common warm-season counterparts, and again modeling and climatology studies have potential to shed light on this question. These studies could help determine what amount and types of data are required to arrive at this understanding (i.e., is current data sufficient, or do we need longer durations or different types of observations than what have been heretofore available). Finally, high-resolution idealized modeling studies of cold season tornadic storms and associated tornadoes that are designed to elucidate the sources of near-surface vertical vorticity feeding tornadoes will have broader applicability to the more general problem of understanding the fundamental mechanisms of tornadogenesis and maintenance across a wide range of environments. Many of these studies would require detailed observations of PBL observations for validation and expansion of existing knowledge, something that would be relatively easy to achieve using a quasi-permanent multi-sensor network.

5. The current Science RoadMap is very light on everything meso-beta and meso-alpha (i.e., 20-2000 km and say 0.5 - 12 h). However, these scales are currently perplexing in forecast and field observing operations. What can/should we do?

EDITORIAL SUMMARY: The consensus of the working group is that a heavy emphasis on modeling studies to understand sources of error and ranges of variability on these scales, as well as impacts on storm development and behavior as a function of this variability, is warranted prior to moving forward with field campaigns. (Note, this seems more true for the meso-alpha scale, as meso-beta at least appears to be *partially* covered by the existing or proposed observation strategies above.) Recent and emerging advances in CAM ensembles and data assimilation are poised to provide a promising way forward in this regard. As a specific example, improving model characterizations and understanding the sensitivity thereof of thermodynamic environments,

particularly in cold season cases where small absolute changes of relevant parameters (such as surface moisture) can lead to large relative changes in CAPE, is something that high-resolution ensemble modeling could potentially provide guidance for future observations. In another example, research on multi-year convection-allowing forecasts shows that current models rarely produce severe storms within low-CAPE/high-shear environments. Efforts to understand these issues need to be fostered. As in #4, many of these studies would require detailed observations of PBL observations for validation and expansion of existing knowledge, something that would be relatively easy to achieve using a quasi-permanent multi-sensor network.

B.5 Working Group on the Mix of Numerical Modeling and Observations

(Corey Potvin, chair)

2018 Update Comments:

An extended-season fixed observational network, supplemented by IOPs, is required to advance our understanding of the structure and evolution of the storm environment prior to and during the development of convection. Existing V-SE observational and CAM datasets should in the meantime be leveraged to inform this understanding, guide the design of the proposed observational network and of IOP strategies, and help prioritize scientific objectives based on the inferred feasibility of obtaining sufficiently accurate and complete observational and model datasets. Outstanding scientific questions include:

1) What features of the mesoscale environment distinguish well between regions of more- versus less-tornadic storms?
2) What features of the storm-scale environment distinguish well between individual tornadic and non-tornadic storms?
3) What boundary layer, upper-air, and storm processes influence these environmental features?
4) How are environmental factors processed during different stages of storm evolution and how does storm life cycle impact the relationship between environment heterogeneity and tornado potential?
5) How well are these processes and environmental features (in particular, the sometimes rapid evolution thereof) analyzed and predicted in current CAMs?

Observing System Simulation Experiments, Ensemble Sensitivity Analysis, data-denial experiments, and model sensitivity studies are promising research methods for addressing these questions. Operations Risk Reduction Exercises to evaluate integrated instrument observing strategies and physical hypothesis refinement is also important to define future observing requirements.

The following material is from the 2017 Science Plan Update:

1. Are reliable strategies available to identify the most sensitive and uncertain aspects of current NWP approaches, so that these issues could be resolved through targeted and relatively easily obtained observations?

We should try to leverage ensemble sensitivity analysis (ESA), which has shown capability to identify synoptic-scale and, to a lesser degree, meso- and storm-scale sensitivities. ESA facilitates identification of critical features that must be better observed and initialized (via DA) in order to reduce analysis/forecast bias & uncertainty. Critical features can also be identified using data-denial DA experiments. Better knowledge of the larger-scale environments for which CAM ensembles perform well or poorly would help guide ESA/data-denial experiments to identify critical features. OSSEs are needed to estimate impacts of new observations (proposed based on above sensitivity experiments), and to optimize the deployment and assimilation of new observations. The “identical twin” problem must be recognized and mitigated. We also need to perform calibrated OSSEs to ensure we are properly emulating observational characteristics.

We must evaluate the ability of current NWP models to simulate PBL processes, both in simpler (e.g., no storms, no terrain) and more challenging scenarios (mesoscale PBL variations around topographic features and other surface heterogeneities). Detailed observations from multiple-Doppler radar and high-resolution PBL to lower atmospheric profiles of wind (mean and turbulent components) and thermodynamics, in addition to documentation of low-level clouds that impact PBL characteristics, will be critical for this. Verification of analyses/forecasts/simulations in unobserved regions is critical, and can be accomplished by assessing sensitivity of analyses/forecasts to PBL and surface scheme choice, and with data- denial DA experiments.

Thermodynamic and kinematic profiling/surface networks are required both to capture important PBL processes in DA and subsequent forecasts, and to validate the capability of current NWP models to capture these processes. Previous work suggests that these observations will need to be numerous to have a major impact. Land surface heterogeneities may make the required number of PBL observations especially large in the SE. Unfortunately, we are a long way from having a dense profiling network, and so it is critical to determine how we can maximize the knowledge gained from the few profiling systems we currently have. Observational requirements should decrease as models improve. We currently need large numbers of observations to force analyses/forecasts off the (biased) model attractor. As model errors decrease, however, observational requirements will be driven more by the scales of the important heterogeneities.

The capability of all of the above approaches to advance knowledge and prediction will be limited in some/all cases by large model biases and failure of data assimilation to analyze critical features. Making microphysics and PBL schemes more flexible (e.g., multi-moment microphysics) in order to better represent complex atmospheric processes would be a major step toward reducing model error.

Collecting a few datasets that focus on densely observing the storm environment and using them to create data-denial DA/prediction experiments would help refine our understanding of the

importance of environment errors to ensemble prediction of storms, and of how strongly the environment constrains storm evolution.

2. Is it feasible to use high-resolution NWP to identify important resolved processes leading to tornado production?

Idealized/toy simulations are useful for advancing knowledge of tornadogenesis processes in a broad sense, but DA-initialized simulations are needed to investigate tornadogenesis in a particular real-world storm and to help ensure that relevant heterogeneities and processes are included. Both approaches can be used to investigate the potential influence of topographic and surface roughness elements on tornadogenesis, and to identify storm-scale tornadogenesis proxies that we can look for in observations, both to validate simulations and refine them (via DA). The value of these insights to real-time observation targeting, however, will be limited by our relative inability to predict when/where storms will form and where they will move. In addition, validation of research simulations at the smallest scales, where their realism is most questionable, will continue to be limited by lacking observations, even with the best achievable V-SE datasets. It may therefore make sense to focus more on verifying models' ability to reproduce storm-scale behavior (e.g., mesocyclone cycling), especially if we consider this a requirement for realistically simulating tornadogenesis.

3. Given the information developed in #2, can those processes then be validated/refuted through a set of obtainable observations, without having to observe multiple, complete chains of events leading to tornado formation (which is probably infeasible)?

Observing entire life cycles of storms likely isn't necessary to advance understanding of tornadogenesis. It's not yet clear what observations, and how many cases, are required to verify model analyses/simulations of tornadogenesis. This partly depends on the degree to which tornadogenesis is dynamically constrained by larger, more observable, scales, and conversely, how "stochastic" tornadogenesis is (e.g., sensitive to turbulent mixing or to subtle differences in intra-storm geometry). Predictability work, including studies external to V-SE, could be useful for exploring these questions and guiding development of deployment strategies that plausibly would provide the required observations. We will hopefully learn more about which observations are needed with each successive field campaign year. Dense surface thermodynamic observations (StesoNet) are promising, but more extensive networks of PBL profiling systems are also needed (including balloon soundings, UAS, and ground-based remote sensing profiling systems such as Doppler lidar, 915 MHz wind profilers, thermodyanamic profilers – both microwave and IR). It still remains to be determined what the effective mix of profiling systems is, given the likely preponderance of low level clouds that will limit the height coverage of the very capable lidar and AERI systems.

Some of the observations we need could be more easily acquired in the Plains, and the resulting knowledge applied in future Southeast field campaigns. While true for internal storm processes, however, the Great Plains do not offer the complex surface features that are common over the SE, making simple extrapolation potentially misleading. Given how few high-quality datasets have been collected in the SE versus the Plains, there's plenty of room for improving our understanding of how tornadogenesis pathway climatology differs in the SE.

4. Repeat the inquiries in #2 and #3, but consider the processes that seem to be associated with such large uncertainty on the meso-alpha and beta scales regarding storm initiation, evolution, interaction, and organization. Corey: this potentially includes considering both: a) the feasibility of using NWP and V-SE obs to learn about the listed processes, and b) the limited practical predictability of storms in the SE, the corresponding limitations imposed on our observing strategies, and the resulting limitations of our ability to collect the V-SE obs required to verify simulated tornadogenesis processes.

It may be easier to study the processes shaping the storm environment and the storm-environment interactions than the intra-storm processes themselves. This would allow deployments to target processes that are more predictable and observable, though the challenge would then shift to collecting observations over a wider range of spatiotemporal scales. In contrast to the "chasing" option available for Plains research activities, longer-term observations over a fixed, comprehensive observational network are required to capture the necessary observations over a range of scales.

5. Assume we obtain fairly comprehensive observations from multiple Doppler radars and several profiling and sounding systems in complex terrain and land use in Spring 2017. Going forward over the next several years, what is an appropriate co-evolution of NWP studies and observing studies to make the greatest progress?

It is certainly important to keep the interaction between NWP and observational studies two-way and in-step. Observations/DA are useful for adding realism to ensembles, but it must be kept in mind that it's possible to simulate storms that look real (at least early on) even without getting the underlying physics right. It will therefore be critical to use the ensembles to identify features/scales that must be better observed in future IOPs so that future simulations can be better validated. Another valuable two-way interaction: microphysical observations should be used to improve microphysical parameterizations, and microphysical output should in-turn be used to identify observations that constrain model uncertainty. To what degree should co-evolution between NWP and observational studies be planned/imposed versus allowing to happen organically?

6. Given all of the above, make specific recommendations for demoting/promoting objectives in the current science plan, grouping them into clusters that could form the basis for focused research campaigns, and add topics (as needed) in the form of specific research questions.

We identified four overarching objectives that should receive higher priority within the V-SE Science Plan (bold). Specific, major recommendations are italicized.

1) Evaluating PBL representation in models. Our highest priority should be evaluation and improvement of NWP model capability to simulate PBL structure and evolution around complex terrain, both in simple and challenging scenarios (e.g., idealized simulations and case studies), using a combination of ensemble sensitivity analysis, data-denial experiments, and physics-sensitivity experiments. Specific questions to address include:

Do models adequately reproduce the characteristics of low-level clouds (e.g., cloud base, cloud fraction, cloud depth) around storms in the SE environment? This is a prerequisite for simulating the wind profile over the PBL.

Are models capable of reproducing the potentially complex flows around terrain features such as Sand Mountain over a range of conditions, including mean PBL wind speed/direction and stability?

Are models capable of representing PBL heterogeneity over a region that has highly variable surface roughness?

How is storm evolution influenced by the underlying surface (topography & roughness)?

At the same time, we need to allow for the possibility that our models will not be sufficiently realistic to advance our understanding of PBL-storm interactions, particularly over complex terrain/land surface characteristics. We should therefore retain a suitably large set of scientific objectives that do not critically depend upon simulating the PBL correctly (e.g., more observationally-oriented studies; NWP/idealized simulation studies that do not focus on storm- PBL interactions) and, speaking more generally, that have hypotheses that can plausibly be tested with our limited observational resources. In addition, NWP studies should adopt a “walk before running” approach (e.g., verify that the undisturbed PBL can be properly simulated prior to trying to simulate PBL-storm interactions).

2) Optimizing use of limited resources. Given the limited number of PBL profiling facilities (2 CLAMPS, 2 MIPS), it may not be possible to obtain enough observations to address PBL scheme deficiencies, or to substantially improve initial conditions for model forecasts. In order to maximize the value of these few facilities, we recommend:

a) Identifying where/when we need better understanding of model deficiencies and positioning facilities accordingly. This can be guided by a combination of emulated observations (OSSEs) and real datasets collected specifically for this purpose.

b) Identifying surface and profiling systems from other institutions that could supplement the current network.

c) Keeping some facilities stationary for months or years to collect long-term datasets. This would greatly facilitate PBL scheme evaluation. These datasets would also facilitate the creation of "nature runs" for use in OSSEs for exploring a number of topics (e.g., predictability, observational requirements/optimization). The datasets would be supplemented by storm-targeting deployments.

3) Investigating storm predictability. We should more highly prioritize efforts to characterize and identify limiters of storm predictability in the SE. While evaluating & improving PBL modeling capability is of the highest concern, we must keep in mind that there could be other, perhaps more significant, sources of forecast error in the SE. Making progress in understanding predictability in the SE will require that our observing network sample mesoscale heterogeneities. We should initially prioritize studies of larger-scale, more predictable phenomena (e.g., storm environment vs. intra-storm processes) since observational verification will generally be more feasible. At the same time, we should investigate to what degree smaller-scale phenomena are constrained by larger scales, since this will help determine which scales we actually need to observe in order to produce simulations/analyses that are reliable enough to be useful for advancing scientific understanding.

4) Improving model physics. We should more highly prioritize concerted efforts to improve parameterization schemes. Beyond hampering operational forecasts, physics errors substantially limit the value of analyses/simulations/OSSEs to advancing scientific understanding. We need PBL/turbulence closure schemes that work better within the "terra incognita". We also need multi-moment microphysics schemes that require less tuning. Improved schemes can be obtained by a synergistic research program in which high-quality observations inform and constrain the development of next-generation schemes, the output of which in-turn guide observation targeting in future deployments.

B.6 Working Group on Improving Use of Existing Operational Data

As part of its annual update to the VORTEX-Southeast (VORTEX-SE) Science Plan, the Science Steering Committee has established working groups to identify gaps in the science plan that could be addressed by VORTEX-SE. This particular working group has been motivated by three broad issues. The VORTEX-SE Executive Committee has expressed concerns about the lack of an emphasis on satellite and lightning data in the science plan. Other agencies, such as NASA, have active research programs in these areas. If there are research topics that are not

being adequately addressed by other agencies, and that bear directly on the Southeast tornado problem, these must be identified.

To address these issues, the working group solicited feedback from a wide range of individuals. These individuals represented the social sciences, research (both government and universities), and operational forecasters from the National Weather Service. Time was a critical factor and this write-up has been assembled through several e-mail exchanges along with a coordination phone call. The write- up below summarizes the discussions to provide the feedback requested by the Science Steering Committee. The recommendations to the Science Steering Committee can be divided into three segments; 1) A greater understanding of the low- to mid-level conditions within the storm, 2) better quantification of the association of lightning with various storm features, and 3) a well-defined path for bringing research results to operations. Inherently, any discussion shows that these three issues are inter-related.

Greater understanding of the low- to mid-level conditions within the storm

Throughout the working group's discussions, this particular topic received a significant portion of the available discussion time. Observations of low- to mid-levels are absolutely critical for dynamics and thermodynamics within storms. This is strongly related to Dr. Kevin Knupp's (University of Alabama) discussions of the impact of topography on storms in the Southeast. The follow-on question to this is how does the thermal profile act in the near-storm environment? With improved observations of the low- to mid-levels, modeling can be better incorporated to analyze the storm environment as well as to test terrain effects.

At this stage, our present modeling is based on Doppler analysis (i.e., the wind field). For VORTEX-SE, this raises a technical question of, do we need more radars to adequately sample storms? This suggests a need for 3-4 CASA style radars allowing for a more focused analysis of the critical low levels. In addition, radar is dominated by scatterers. Are we able to understand other microphysical parameters that cannot be directly observed through the wind field? This is where lightning observations can be used and will be discussed in more detail in the following section.

Overall, this section provides the over-arching theme for the working group's feedback and subsequent sections. The relevant questions for VORTEX-SE are:

- How can we better observe the low- to mid-levels of the storm and near-storm environment?
- Does this require more radars and/or a local CASA radar network?
- How does the thermal profile character of the 0, -10, and -20°C isotherms act in the near-storm environment?
- Improved observations can then directly support modeling efforts.
- A better understanding of downdraft formation.
- What is the nature of the downdraft versus the environment? A spectrum of storms should be observed, both for storms that produce tornadoes as well as null cases.

- Emphasis in previous discussions has been on supercells but the southeast has many tornadoes in non-supercell storms, such as QLCS systems.

The investigation of tornado genesis should not occur without a similar investigation of the null event.

Better quantification of the association of lightning with various storm features

VORTEX-SE does have the ability to take advantage of several unique lightning observation systems. Currently available are the ground-based lightning mapping arrays (LMAs) in north Alabama and Atlanta covering the primary field campaign locations. Additionally, a network at Kennedy Space Center is installed, but access needs to be obtained. The GOES-16 Geostationary Lightning Mapper (GLM) is now online in the GOES-East position and undergoing final validation. Therefore, GLM observations will be available during future field campaigns, as they were for part of the 2017 VORTEX-SE field campaign. VORTEX-SE may also benefit from additional observations that will occurred during the GOES-R calibration and validation campaign in 2017.

The working group aimed to address one of the concerns of the Executive Committee, specifically the relative lack of lightning data in VORTEX-SE. The discussions reflect the overarching theme of the section above as well as the unique capabilities offered by the LMAs and GLM.

Lightning is already being used from an applications standpoint with respect to severe weather (i.e., lightning jumps as a precursor). Lightning cannot delineate between the type of severe weather, such as tornadoes, but indicates that a favorable environment has been realized in such a way as to produce an updraft that extends into the cloud's mixed-phase region. The forecaster must have an understanding of the environment to identify the specific severe weather threat. Furthermore, based on an understanding of lightning formation, which is driven by the strength/volume of an updraft in the mixed-phase region of a storm, operational forecasters can obtain general information on which updrafts are intensifying and which are weakening. The relative magnitude of flash rate change with respect to the fluctuating background (the lightning jump sigma level) helps to identify particularly significant changes to the mixed phase updraft. In this way a forecaster may discriminate among cell fluctuations and identify those that are most significant; statistically, these significant fluctuations (jumps) have been shown to be associated with severe weather production. This shows the utility of the lightning observations in understanding storm state but these observations are still indirect indicators. The primary goal recommended by the working group is to quantify this relationship to several features listed below. Understand lightning with respect to tornado genesis, mid-level formation of precipitation, and the impact/delineation to the formation of the downdraft.

- Preliminary work has shown that this is totally environmentally context driven. E.g.: A high shear, low CAPE environment such as a book end vortex in a bow segment can generate a tornado but is unlikely to have significant lightning.

- This requires the observation of a spectrum of storm cases, both with storms that generate tornadoes and null events. Better define and link the various hypotheses of lightning electrification to microphysics/dynamics to the formation of a tornado.
- Is there an inherent limit to how far we can go with lightning to tornado genesis (i.e., can we be more specific than the current trend method)?

What is the impact of terrain on lightning and subsequently tornado genesis? We must look at links of lightning and downdraft/dynamics formation.

- How does the lightning signature relate to the context of the current environment?
- There needs to be priority for environmental classification.
- Compare and contrast different environments with lightning characteristics.
- How well does lightning variability correspond to variability of convective storm microphysics and dynamics, especially as taught in forecaster warning decision training?

Another issue pertains to the physical science of storm initiation. Tools are being developed within the GOES-R Proving Ground to address convective initiation as well as lightning initiation. This is important, particularly for emergency managers who need reliable information on the initiation of lightning in proximity to sensitive locations and events. This has equal use for ground stop activities at airports. The issue is that end users, such as the emergency management community have practical considerations at time scales beyond the state of current convective forecasting.

An example given to the working group involves emergency managers requiring information 5 hours prior to severe weather so that a fire department can determine personnel availability and equipment readiness. At 3 hours prior, search and rescue equipment is retrieved from storage. At 2+ hours out, changes in school dismissal times are made and must take into account bus route times. Lastly, it takes 18-60 min to clear most types of lightning sensitive venues.

What can be done to enhance to temporal fidelity of convective forecasting? These are issues partly being addressed by projects such with the GOES-R convective initiation, UAH lightning initiation, and CIMSS ProbSevere as well as efforts to develop probabilistic warnings and storm tracks.

The working group raised a further issue that may be outside the scope of VORTEX-SE, but is important to consider. Are there specifics to the lightning and electrification process that is key to the Southeast versus the Plains? In other words are lightning characteristics for tornadic storms, and conversely null events, similar across the country or are there regional differences? This requires gathering data for VORTEX-SE and then analyzing cases from separate regions. The most likely sources of data would be events that occurred within the field of view of the Oklahoma and West Texas LMAs during VORTEX-2 as well as from the older STEPS field campaign.

A more involved effort can investigate cases from these LMAs during their lifetime outside field campaigns. If this were done, additional LMAs could be used, such as from the Washington D.C., Colorado, and Houston networks. An advantage of the Oklahoma, West Texas and Colorado networks is that they will serve as calibration and validation sites for GLM as well as Huntsville and Kennedy Space Center. The GLM also offers the ability to monitor all of these regions, and many more, with a single instrument for regional comparisons. A regional inter-comparison would:

Repeat all of the lightning discussion above to investigate the regional differences.

Compare and contrast lightning characteristics here with other regions, such as the intra-cloud and cloud-to- ground flash ratio. Are pulses (Earth Networks), LMA sources and flashes, or radiance energy (GLM) the same everywhere or are there differences? How can this information be optimally blended while not overwhelming a forecaster?

A consideration of the regional differences is not without merit, as this is partly the premise for VORTEX- SE itself. Early work to use lightning to infer microbursts further supports this. Here, early work showed a good relationship between lightning and downdrafts in the Southeast. That same relationship did not work at all in the High Plains.

The launch and subsequent activation of GLM offers some additional opportunities, although the NASA ROSES A.25 call is addressing GLM activities. As stated earlier, the GOES-R calibration and validation campaign occured during the latter part of the 2017 VORTEX-SE campaign, and extended beyond the VORTEX-SE dates to June 18. With this work, additional equipment or observations were available to VORTEX-SE. This includes observations from the ER-2 research aircraft, an interferometer, and likely the HAMMA field mill network.

A well-defined path for bringing research results to operations

Our National Weather Service (NWS) partners on the call indicated that a robust research to operations plan needs to be created in order to transfer results from VORTEX-SE to the operational forecasters.

The direction this must take needs to be developed, but must keep in mind that the focus needs to be on what the NWS will have available and not just what is in the field campaign. Although some of the local forecast offices have extensive experience with LMAs, these are limited to only a few locations and therefore, results will need to focus on some combination of National Lightning Detection Network, Earth Networks, and/or GLM observations.

Earlier work with total lightning has shown cases where concepts like the lightning jump may not be valid. This can be in a high shear, low CAPE environment where updrafts do not significantly reach the mixed-phase region. Additionally, the bookend vortices in a bowing line segment may show little lightning signature ahead of a tornado, whereas elsewhere in the line a lightning jump may occur signifying a strong updraft that may become part of a severe storm. Tropical

cyclones may present another case in the rainbands where seeing lightning may differentiate a cell of concern compared versus other cells.

With this in mind, there is both the science and sociological task of working with operational forecasters to have them routinely think:

“Given that I have a threat of severe storms and tornadoes today, and based on the pre-/near-storm environment and anticipated convective mode, what is the likely signature for storm-based lightning as either a warning decision making weight and/or discriminator?”

Given these research to operations considerations, the working group poses the following. Develop a plan to bring results from VORTEX-SE to operations. This requires identifying who to do this as well as a means to vet the results.

Who is responsible for research to operations transitions?

- Guidance by the NWS Operational Advisory Team (NOAT)? NWS Total Lightning Working Group (TLWG)?
- The collaborative institutes CIMMS, CIMSS, CIRA, CICS-MD, NASA SPoRT?
- Leverage a position similar to the GOES-R and JPSS proving ground satellite liaisons?
- Sustain relevant pieces of the GLM Science Team, which encompasses experience with all forms of lightning data and the challenges related to operationalizing them?

How will training be performed?