Pushing the Boundary (Layer): An Initiative for Boundary-Layer Research in the National Weather Center Community

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Executive Summary
The institutions that comprise the National Weather Center (NWC) community have been historically recognized as prominent leaders in severe weather research, radar meteorology, and mesoscale to stormscale prediction. As the scientific landscape evolves, so does the focus and strength of research institutions like ours. At its inception, the NWC became a model for how research and collaboration can lead to societal impacts. Leveraging this strength, ***the NWC community is poised to lead a new effort in boundary-layer meteorology on national and international levels.***

State of Boundary Layer Research in the NWC community
Several institutes and collaborative groups within the NWC community have already contributed important work in boundary-layer and boundary-layer-related research areas. For example, collaborative efforts between the University of Oklahoma (OU) School of Meteorology (SoM) and the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL) have resulted in the development of two state-of-the-art mobile boundary layer profiling systems (CLAMPS). However, there are key areas where renewed focus and investment would elevate the NWC community to international leaders in boundary-layer research. One such area is expanding the collaboration and communication between modeling and observing communities in the NWC. Additionally, engineering support for operating and maintaining instrumentation is needed.

Relevant Science Goals
We separated science goals into short, medium, and long-term time horizons based on compiled and interpreted results from a community survey and a series of focus groups. These goals, all centered around boundary-layer science, span a range of applications and spatiotemporal scales.

Looking to the future
Training and recruitment of a new generation of scientists interested in boundary-layer research is essential for this initiative to be successful. Currently, the pool of well-trained and interested students and early-career scientists is severely constrained. This shortage can be addressed by community building within and outside of the NWC, such as through the Boundary Layer Integrated Sensing and Simulation (BLISS) group. This initiative also requires a number of additional resources (e.g. computing, engineering support) and a method to track and quantify its progress.

Recommended actions

1. Continue to support and expand the observational capabilities of the NWC community.
2. Support existing, and initiate new, collaborations across institutions, agencies, and labs—both internally and externally.
3. Review hiring and recruitment plans to make sure that we invest in, and develop, new talent to expand scientific expertise and to build a diverse and inclusive research environment.
4. Improve the "branding" of boundary-layer science in the NWC and broader communities.
5. Get more researchers working with, and familiarized with, novel observations and modeling tools.
6. Expand collaboration and develop genuine overlap between modeling and observing teams.
7. Find ways to exchange knowledge and develop new expertise, both in training and among established scientists (e.g., summer school)

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Introduction

The boundary layer is the lowest portion of our atmosphere that is in contact with, and influenced by, the Earth's surface. Most importantly, this is the part of the atmosphere in which we live and directly impact though human activity. Conditions in the boundary layer not only shape the weather, they can also determine health outcomes and quality of life (e.g., heat waves, air quality, disease spread). Boundary-layer environments are also important in the context of harnessing renewable resources, such as solar and wind power. Here in Oklahoma, large wind energy production installations have dramatically increased over the past 20 years. Mitigation of the impacts associated with climate change is also critical to Oklahoma, as agriculture and other industries face evolving risks and challenges. The growing needs of society make it clear: we need improved observations, understanding, and prediction of boundary-layer phenomena.

Over the past ten years, the National Research Council has published multiple National Academies of Sciences reports that partially attribute limits of current knowledge of lower-atmospheric phenomena to limitations in observing capabilities, and that call for improved observations of temperature, humidity, wind, and cloud characteristics in and near the boundary layer. In particular, these reports call for a new ground-based network of such observations (National Research Council 2009, 2010). Wulfmeyer et al. (2015) made similar recommendations in a review of remote sensing of the lower troposphere. More recently, the 2017–2027 Decadal Survey (National Academies of Sciences, Engineering, and Medicine et al. 2018) has instigated interest in possible space-based solutions for observing the boundary layer.

Widely deployed operational observation networks in the United States routinely monitor near-surface conditions (e.g., ASOS networks and mesonets) and conditions at heights of one kilometer and greater above the surface (e.g., weather radar and satellite observations). The intervening layer represents the the boundary layer, where observations are few and far between. One common observation dataset collected in this portion of the atmosphere comes from balloon-borne packages, or radiosondes. However, operational radiosonde stations are located ~500 km apart and are launched only twice per day (Melnikov et al. 2011). Another dataset is the AMDAR aircraft data. However these primarily comprise temperature and wind, while water vapor observations are limited (only about 10% of aircraft have water vapor observation capabilities; Zhang et al. 2019; Moninger et al. 2010). These profiles are not collected at all airports and are "flights of opportunity", which results in poor diurnal sampling. An obvious observational gap exists.

Numerical weather prediction (NWP) plays a key role in the relationship between boundary-layer observations and theory. Observations can inform theory and be used to validate numerical model output. Meanwhile, NWP can guide observational strategies and fill in the physical and temporal gaps of our observing capabilities to improve physical understanding of boundary-layer phenomena. This relationship between observations and models will only be enhanced over the next decade, as climate models start to approach the resolution of regional weather forecasting models and weather forecasting models approach the resolution of large-eddy simulation (LES). Historically, boundary-layer parameterizations used in NWP models are applied as one-dimensional column models under the assumption that turbulence is steady-state and horizontally homogeneous, and that the ensemble of boundary-layer motions are fully contained within each column as subgrid-scale phenomena. These assumptions are problematic on at least two fronts. First, as NWP grid spacing approaches 1 km and smaller, representation of boundary-layer flow features within the corresponding horizontal scale ranges poses an issue because such scales are often within the maximum energy-containing spectral intervals of boundary-layer motions. This means that the flow features are likely not sufficiently resolved explicitly nor correctly represented statistically (Wyngaard

2004; Gibbs et al. 2011). Recent work (e.g., Shin and Dudhia 2016) has focused on adding scale awareness to boundary-layer parameterizations so that subgrid quantities are functions of grid spacing as it relates to physical scales of the boundary layer. The second issue is that the theoretical underpinnings of these schemes are based on steady-state observations and simulations (LeMone et al. 2019). However, we know that capturing the effects of heterogeneity and features associated with evolving boundary layers (e.g., advection) is important to numerically representing the boundary layer. There is a need to combine observations and simulations of evolving boundary layers to extend and rethink the models that form the basis of boundary-layer parameterizations (LeMone et al. 2019). Another complicating issue is the use of different boundary-layer schemes in forecast ensemble systems, which are routinely underdispersive (Flora et al. 2019). Recent internal work at the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL) has been proposed to introduce physically based stochastic perturbations in the boundary-layer schemes to improve reliability (i.e. probabilistic output), which are used in combination with scale-aware boundary-layer parameterizations to improve the resolution (i.e., the deterministic skill of a given member).

Together, the institutions that comprise the National Weather Center (NWC) community[1] have been historically recognized as prominent leaders in severe weather research, radar meteorology, and mesoscale to storm-scale prediction. As the scientific landscape evolves, so do the focus and strengths of research institutions like ours. At its inception, the NWC became a model for how research and collaboration can lead to societal impacts (Fig. 1). Leveraging this strength, the NWC community is poised to lead a new effort in boundary-layer meteorology on national and international levels.

There are several open research questions under the umbrella of boundary-layer research relevant to the NSSL mission[2] and to the interests of the broader NWC community. Improved understanding of boundary-layer processes can impact numerical Earth system modeling from direct numerical simulations to coarse global models. Boundary-layer science can enhance prediction on sub-hourly timescales to climate timescales. There are important questions about surface-atmosphere interactions (e.g., land-atmosphere, sea-atmosphere, ice-atmosphere) that are critical to understanding the impacts of a changing climate. Given our wealth of observational assets, Oklahoma's evolving land use, and the effects of climate change happening in our region, we are well-poised — and it is practical — to become a lead institution for advancing the understanding of land-atmosphere processes. Such improvements and accurate boundary-layer representation are necessary to make seasonal-to-subseasonal prediction a reality. As observational and numerical capabilities improve, it is clear that a more complete understanding of the role of boundary-layer processes is necessary to advance understanding of storm dynamics and morphology. Just this limited sampling of boundary-layer-related research topics shows that every institution in the NWC community has a vested interest in the advancement of boundary-layer science.

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[2] The National Severe Storms Laboratory serves to enhance NOAA's capabilities to provide accurate and timely forecasts and warnings of hazardous weather events. NSSL accomplishes this mission through research to advance the understanding of weather processes, research to improve forecasting and warning techniques, and development of operational applications. NSSL transfers new scientific understanding, techniques, and applications to the National Weather Service.

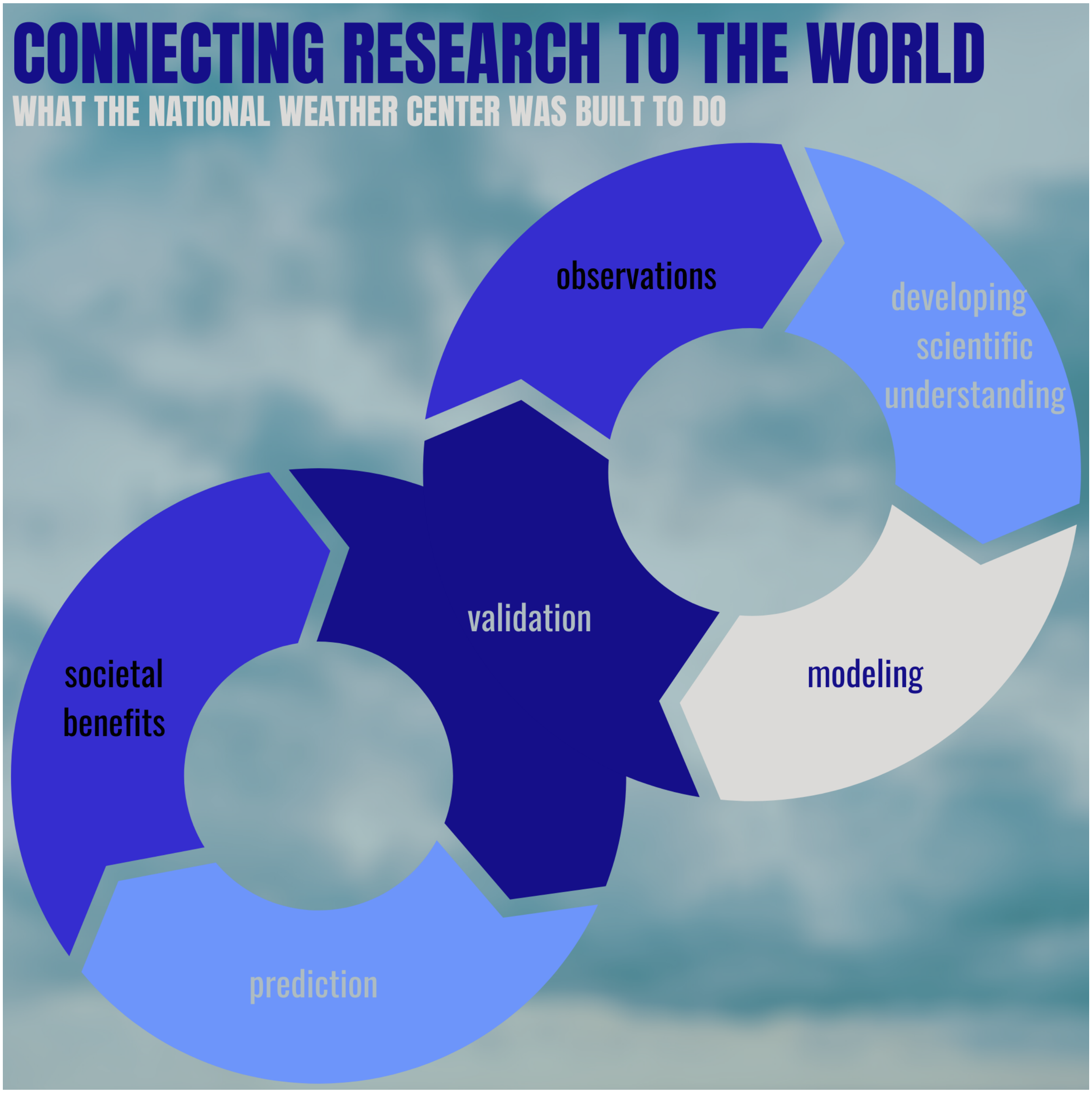

Figure 1. The combination of academic and research partners in the National Weather Center are prepared and capable to lead a new effort to bring boundary-layer science to the broader community. Adapted from Stith et al. (2019).

Community approach

The information contained within this document was gathered in a variety of methods, which we briefly explain here. After a review of the literature and recent national and international reports, the authors designed a short questionnaire and shared it with a small (>5) sample of individuals within the NWC community to gain insight on the current thinking about boundary-layer research. This questionnaire asked only three questions:

1. What are the big outstanding questions you see in terms of boundary-layer science (short term—within 5 years, and long term–beyond 5 years)?
2. What tools have been used or are currently being used to address these questions (observation-based and model-based)?
3. What tools or fundamental knowledge do we need to better address outstanding questions and move this science forward?

Using the feedback from this questionnaire and our own perspectives as early-career boundary-layer researchers in the NWC community, we developed a draft version of this document and shared it with the community. A seminar was delivered (recording available online) to introduce the initiative to the community and solicit their feedback.

Given the current COVID-19 mandated telework conditions, a workshop approach was not feasible for this endeavor. Instead, we held four small focus group sessions. We invited specific members of the community to participate in these four sessions to ensure a diversity of research area, background, perspective, and career stage. We also held one open feedback session where any community members could provide their feedback on the concepts and ideas presented. The information generated by these sessions greatly improved the scope and content of this document, and we are deeply appreciative of all the community members who participated in this process.

State of boundary-layer research in the NWC community

Several institutes and collaborative groups in the NWC community have already contributed important work in boundary-layer and boundary-layer-related research areas. There are key areas where renewed focus and investment would would elevate the NWC community to international leaders in boundary-layer research. Community strengths and gaps are described here to inform on areas important for continued support and new focus.

Community strengths and assets

Given the long history of the NWC community in the realm of radar meteorology and severe storm science, it is unsurprising that this community remains a global leader in observation technologies and applications. These strengths serve as the pillars on which a new nationally and internationally leading boundary layer initiative can be built. A sample of NWC community observation capabilities is offered in Table 1.

Since 2015, collaborative efforts between the University of Oklahoma (OU) School of Meteorology (SoM) and NOAA NSSL have resulted in the development of two state-of-the-art mobile boundary layer profiling systems. These systems have participated in well over a dozen field campaign and have collected thousands of hours of boundary layer kinematic and thermodynamic profiles. In the last two years, NOAA NSSL has nearly doubled its boundary layer profiling capability. The Field Observation Facilities Support group at NOAA NSSL have supported continued deployment and development of new and established observation platforms including the vehicle-based mobile mesonet platform and balloon-borne observations. Additionally, NOAA NSSL has developed a new small team specifically focused on boundary-layer research questions. This step has already led to lead or collaborator roles on boundary-layer projects totaling nearly $1 M in funding in just the last year. With the right investment in equipment, people, and projects, a lot can happen in a short time. We are collaborating with universities and other national labs on major na-

Table 1. A basic sampling of boundary-layer relevant observation capabilities of NWC community partners.

Platform	**Observation Type(s)**	**Operator**
ASSIST	Thermodynamic profiling	NSSL
CLAMPS	Kinematic profiling Thermodynamic profiling Surface meteorology Aerosol backscatter	OU SoM (CLAMPS1) NSSL (CLAMPS2)
CopterSonde	Kinematic profiling Thermodynamic profiling Constituent measurement	OU CASS
Doppler Lidar	Kinematic profiling Aerosol backscatter	NSSL
Flux Station	Turbulent fluxes Radiative fluxes	OU SoM
Mesonet	Surface meteorology	OK Mesonet
Mobile Mesonet	Surface meteorology	NSSL
Mobile Radar	Radar reflectivity Radial velocity Dual polarization variables	OU ARRC OU SoM NSSL
Radiosonde	Kinematic profiling Thermodynamic profiling	OU SoM (iMET) OU CIMMS (swarm sonde) NSSL (Vaisala)
Tuffwing	Kinematic sampling Thermodynamic sampling Constituent measurement	OU CASS

tional initiatives and have potential to grow these collaborations into strategic partnerships. NOAA NSSL is now prepared to move ahead with boundary-layer research spanning basic science to applied problems and transition from research to operations. Current research themes include boundary-layer observation methods, boundary-layer and turbulence parameterization across scales, near-storm boundary layers, and convection initiation.

Prior and recent developments have also included important boundary-layer efforts within the College of Atmospheric and Geographic Sciences at OU. The formation of the OU Center for Autonomous Sensing and Sampling (CASS) has led to the new development of uncrewed aircraft for boundary layer sampling, enabling high temporal resolution in-situ profiling. CASS continues to innovate and produce cutting-edge airborne technologies enabling new and improved observation options. At the SoM, multiple faculty have focused on boundary-layer and boundary-layer-related research problems. At present, the most prominent research themes in the SoM are in land-atmosphere interactions, boundary layer and turbulence dynamics, analytical and numerical modeling, and boundary-layer observation. These efforts are also training a new generation of scientists with an interest in boundary-layer problems. OU also maintains the Kessler

Atmospheric and Ecological Field Station (KAEFS). KAEFS is located 28 km southwest of OU's main campus and is meant to serve as a venue for transdisciplinary research. Multiple academic units use KAEFS for long-term observational experiments.

Elsewhere in the NWC community, radar observation methods continue to be developed and applied to new problems, ranging from tropical systems to clear air sampling and many things in between. Operational forecasting agencies also have an interest in collaborating to implement boundary layer observations into their toolboxes in order to keep pace with the state-of-the-art. The Oklahoma Mesonet remains the gold standard for high spatial resolution surface measurement programs in the United States. This resource and partnership is priceless in our efforts to expand our boundary layer research portfolio.

Of course, observations are not the only tool important for boundary-layer research efforts. Across the NWC community, there are several groups and researchers developing and improving standout NWP systems. This includes state-of-the-art convection allowing models (e.g., NSSL Warn on Forecast System [WoFS]) and modern data assimilation tools. There is also a focus on forging ahead in the transition to a unified forecast system, which leads and contributes to national goals. Our local expertise is crucial to a successful and well-rounded boundary-layer research effort. Combined with the College of Atmospheric and Geographic Sciences, the NWC community is able to model phenomena across a range of scales.

Community areas for growth

Within NOAA NSSL (inclusive of OU Cooperative Institute for Mesoscale Meteorological Studies [CIMMS] personnel), boundary-layer science is undergoing a renewed period of focus and growth. Three early career scientists have joined NOAA NSSL to focus on boundary-layer observation and boundary-layer parameterization in convection-scale modeling. While this team is rapidly developing a research portfolio, additional support from current and future NSSL scientists is necessary to meet our goals. Even during this renewal, internal focus on basic research is still limited. For instance, the WoFS is still heavily focused on verification despite the need to fundamentally improve models by leveraging, e.g., new observations. It remains critical to support basic research efforts in addition to applied and research-to-operation projects. This is a work in progress.

In the academic units, recent retirements and career transitions have depleted the number of faculty focused on boundary-layer and boundary-layer-related topics. In the interest of both broadening areas of expertise and maintaining historical strengths of the academic programs, such as those at the SoM, an investment and focus on boundary layer meteorology is key. As observational and numerical capabilities continue to grow, many problems once considered mesoscale or storm-scale are now recast as boundary-layer problems. As educational demands change, a shift away from classical math and physics coursework toward more applied options is apparent across the field of atmospheric science. This all results in a dearth of interested, qualified, and prepared students to enter the research community in these critical spaces. This is a local and more community-wide issue that needs immediate attention. Existing courses need to be updated and made available more frequently, while new courses should be developed as appropriate. The NWC has unique opportunities to innovate graduate education and workforce development for our profession. All recent graduates with experience in boundary-layer observations and modeling were highly sought after and recruited to prestigious positions before they completed their graduate degrees.

While the NWC community's observational capacity is large, it at present is mostly focused on remote-sensing and ground-based instrumentation. CASS is developing uncrewed aircraft capable of collecting in-situ measurements and radiosondes continue to be used, but other in-situ observation platforms are not maintained in the NWC community. It is important for this community to find and leverage new and existing collaboration with other instrumentation pools (e.g., NSF, NOAA) to utilize platforms enabling in-situ observations, such as crewed aircraft.

Across all partners in the NWC community, efforts to enhance and expand capabilities of NWP across temporal and spatial scales are ongoing. Expanding the existing collaboration and communication between the modeling and observing communities is needed. Additionally, researchers in the NWC community continue to make use of existing data that may help identify outdated or misapplied concepts, explore new topics, or merge existing concepts in support of this collaboration. There is also a lack of unique boundary layer products or niches associated with the NWC, which only further hinders positive marketing of the community to a broader audience. Creative solutions are needed in these areas since funding of basic research is more difficult to obtain. Specifically, researchers need to expand the pool of targeted funding agencies and look for opportunities to conduct basic research in projects that support broader next-generation societal needs.

Of course, none of these improvements are possible without the expansion and improvement of supporting resources. There is a need for more engineering support from fields other than radar to help develop and operate instrumentation as observational capabilities expand. Similarly, researchers commonly feel that computational resources in the NWC community are lacking. These computational tools need to keep pace as hardware demands and numerical problem sizes continue to grow at a rapid pace.

Relevant science goals

Given the aforementioned strengths in the NWC community, both realized and potential, there are several relevant and timely science goals that we are well-suited to address. Gathered through the compiled and interpreted results of a community survey, several goals are presented here. These are split into short-, medium-, and long-term goals. Short-term goals are those thought to be achievable or largely advanceable within five years. Medium-term goals include efforts that begin within five years and require longer timelines. Finally, long-term goals are the scientific undertakings envisioned after five years, which shape the future of boundary-layer research.

Short-term goals

1. **Updating parameters and empirical relationships in the boundary layer**

   Many of our boundary layer and turbulence parameterizations rely on estimated values of parameters or empirical relationships derived from decades-old observations and are intended for O(10km) grid spacing. New observation capabilities enable us to renew and update such estimations and relationships. More importantly, statistically relevant datasets are needed to inform on the physical range of such parameters and relationships for the development of stochastic and/or scale-aware parameterizations. Such efforts should assist parameterization efforts for land-surface models, surface-layer parameterizations, boundary-layer parameterizations, and more.

   This requires long-term targeted campaigns to collect specified observations in several regions and regimes, providing samples from which statistics can be computed. This approach would diversify the applicability of parameterization and modeling beyond our current capabilities. This is a different mode than is often employed by field campaigns in which many NWC community partners participate. Some example variables or parameters of which such observations are needed include turbulence kinetic energy, energy dissipation rates, turbulent fluxes, surface-layer wind profiles, and more.

Improved NWP, from storm-scales to climate-scales, *requires* adequate boundary-layer parameterization. It is important to note that improved boundary-layer parameterization also require improved land-surface models and surface-layer schemes. We need these observations to make such improvements and to understand the related system benefits of the improvements.

2. **Nocturnal convection initiation**
   The initiation of new convection during the overnight hours remains poorly understood. Given the large amounts of existing data (e.g., PECAN observations and other CLAMPS datasets), this problem is one we can address without an urgent need for new field missions. Theory development is already robust within the NWC community (e.g. Shapiro and Fedorovich 2009; Reif and Bluestein 2018; Gebauer et al. 2018; Shapiro et al. 2018; Smith et al. 2019). Capitalizing on existing expertise and uniting existing ongoing efforts is necessary. With our local assets, conceptual models of convection initiation at night are in reach.

3. **Thermodynamic profiling improvements**
   At present, we are capable of observing bulk boundary-layer profile characteristics given good observing conditions and sufficiently long time-series observations. Our current capabilities are insufficient to provide the needed resolution to observe important fine-scale profile evolution in the boundary layer. We are particularly deficient in our ability to observe boundary-layer moisture. Dedicated efforts to increase our observation capabilities in this area and improve thermodynamic retrieval methods are needed to improve our ability to observe boundary-layer features and evolution important for convection initiation, environmental conditioning for high impact weather, and model validation.

4. **Near-storm environment observations**
   This goal has multiple components. First let us focus on the development of kinematic observation capabilities. Analogous to thermodynamic profiling improvements mentioned above, improving our ability to characterize flow in the boundary layer is critical, especially to storm science. Mobile assets are tremendously valuable for studies of the near-storm environment itself and for validation of models in this otherwise observation sparse region (see Laser 2020). Methods are needed to capture small-scale variability in a rapidly evolving environment.

   It is also crucial that conceptual models are updated as more is understood to develop more targeted observation strategies. As fine-scale numerical modeling becomes viable, new features are hypothesized to exist. It is important to develop realistic and intentional strategies to verify such hypotheses.

   One way to accomplish this is through the development of robust observation simulators (e.g., SimRadar developed in part by the OU ARRC Cheong et al. 2017) which can model a variety of atmospheric conditions on large-eddy simulation (LES) scales and prognosticate the observation targets (e.g., aerosol distributions in the case of Doppler lidar). It is important to know if these features are observable in principle. Such tools can be used to learn more about the environments of interest (e.g., density current and cold pool interfaces, QLCS wind shear profiles, supercellular dynamic features), and also to revolutionize the way we observe near- and pre-storm processes.

Another area of interest which can be addressed via near-storm observation is storm-environment relationships. There is a need to examine the impact of environmental changes on storm evolution in convection-scale NWP. This requires more understanding also of how storms modify their environments, including observational and idealized modeling approaches. These strategies can also be applied to quantify and evaluate model representation of the role of the evening transition and nocturnal low-level jets on thunderstorm enhancement.

Finally, thunderstorm inflow and outflow are both areas of interest for boundary-layer study. Recent observations (i.e., Doppler lidar observations in the near-storm environment from TORUS2019) suggest the inflow region is not as homogeneous as once thought. Additional study is needed to quantify and understand such heterogeneity. For example, how do we separate existing boundary-layer structures and internal boundaries from storm-induced modification? Such small-scale heterogeneity may also suggest the need for *lateral* communication between columns in surface-layer and boundary-layer models. Thunderstorm outflow is a source of turbulence generation and can play an important role in storm morphology, longevity, and new initiation. Observations in this region can improve conceptual understanding and numerical representation of the processes.

Medium-term goals

1. **Convection initiation**

   Prior research has attempted to understand the mechanisms of convection initiation. While understanding and conceptual models have been developed on the mesoscale, additional verification of this understanding is needed. Additionally, we now have the observational and numerical tools needed to approach the convection initiation problem on a finer, more local, and even parcel-based scale.

   Given our location in the country, it makes sense to start first with dryline-associated convection initiation. With modern observational and numerical methods, we can move ahead with characterizing parcel residence time in dryline circulations, understanding the motions that support successful convection initiation, and exploring the conditions leading to convection failure. For example, we can evaluate where along the dryline convection is favored. We can also explore if convection failure is related to boundary-layer processes, dry-air entrainment from the free troposphere, or larger-scale processes. In order to answer such questions, a new field program is needed. Using state-of-the-art platforms, we can elucidate convection initiation processes via detailed multi-Doppler four-dimensional airflow and trajectory analysis from the inflow environment through local mesoscale updraft to storm formation. The tools to accomplish this task exist today, but new and focused collaboration and efforts are needed for this approach.

   Once understanding and conceptual models are developed about drylines, these results can be scaled to other forcings believed to play an important role in convection initiation, such as non-dryline airmass boundaries, sea breezes, urban boundaries, cold pools, outflows, or density currents, and other initiation mechanisms. The similarities and differences of convection initiation processes spanning the parameter space of surface-based drylines, cold fronts, and non-classical mesoscale circulations could be determined in this framework.

   Some efforts in this area are already in planning or are underway. For example, a recent cross-institution team was awarded funding to participate in the DOE-ARM TRacking Aerosol Convection interactions ExpeRiment (TRACER) with a focus on the role of aerosol, sea breezes, and urban boundary layer circulations on convection initiation. Even so, measurable advancement in the science of convection initiation is expected to take additional collaboration and several years to accomplish.

2. **Boundary-layer properties important for renewable energy resources**
   As society increases its demand for renewable energy resources, Oklahoma has become a popular location for renewable energy generation installations. In the last 20 years, the number of wind turbines has greatly expanded in Oklahoma. The relationship between boundary-layer processes and renewable energy resources is multi-faceted. There is the obvious need for prediction of low-level wind magnitudes and potential events that may impact wind turbine energy generation rates or even put the wind turbines at risk for damage. It is also crucial to accurately predict the efficiency of solar power generation, which would include boundary layer properties such as those leading to cloud formation or aerosol loading near the surface. This opens an opportunity for partnerships with national labs (e.g., Department of Energy labs) and private stakeholders. Some initial groundwork has already been laid through collaborations with scientists from the Department of Energy's Lawrence Livermore National Laboratory, most recently through a partnership in the American Wake Experiment (AWAKEN) campaign. This partnership has included research support and funding for graduate students at OU SoM. This example could be extended to additional projects and to include new strategic partnerships.

3. **Robust observation technique development**
   As mentioned under *short-term goals* item 4, the development of robust observation simulators would be useful. Here we use simulator to describe a numerical tool that models atmospheric conditions *and* simulates the observation hardware techniques directly. For example, a Doppler lidar simulator would model boundary-layer flow and the motion and distribution of aerosol that act as targets for Doppler lidar scans. A simulated Doppler lidar observation would use the same observation principles as the real platform, enabling us to determine if various phenomena are observable given platform specifications. Such simulators are needed for all instruments operated in the boundary layer (e.g., Doppler lidar, microwave radiometer, atmospheric radiance interferometer, swarm soundings, radiosondes, uncrewed aircraft, radar, and more). While some work on such tools can and should begin soon, time will be needed to develop a full suite of simulators. These simulator tools are important for several reasons. They can help us quantify the error of observing systems, important for instrument design, data processing, and data assimilation efforts. Additionally, simulators can help us find optimal ways to leverage growing boundary-layer observation capabilities for a range of applications and scales. Using simulators can inform observation targets and strategies for field campaigns, reduce costs, and hopefully increase positive results. Observation simulation sensitivity experiment frameworks in NWP models could also benefit from synthetic observations developed by robust simulators. It could also help us determine how ground-based observations may be leveraged in support of a space-based observation solution for boundary-layer monitoring. We could also use these tools in the development of recommendations for next-generation operational observing systems required to improve mesoanalysis and nowcasting, serving operational needs for protecting life and property.

   In addition to the development of simulators, we also need to invest time and effort in the development of more complex observing options with the instruments we already have. Following the same Doppler lidar example, given multiple lidar platforms, it becomes possible to conduct targeted scan patterns. Virtual towers, dual-Doppler lobes, rapid-scan vertical slices, and slant stares all should be explored. Similar goals can be described for most operating observing platforms in the NWC community. This includes efforts to combine datastreams from multiple platforms in the creation of value-added products. For example, what are the benefits of coordinated operation of a CLAMPS-like platform and uncrewed aircraft sampling? Thus far, we have only scratched the surface of what is possible with our current state-of-the-art capabilities. There also should be continued focus on expanding our capabilities by evaluating and investing in relevant platforms to meet our goals.

Lastly, it is critical to maintain and build strategic collaborations—both inside and outside of the NWC community. Various institutions have specific capabilities and expertise. The science of boundary-layer observation is evolving quickly. Bringing expertise together can enable us all to explore new research avenues and develop the future of boundary-layer science *together*.

4. **Expansion into applied boundary-layer fields**

   As funding for basic research becomes more difficult to obtain, it is critical to expand our participation and collaboration in applied fields that depend heavily on boundary-layer processes. Failure to do so may mean that we lack preparedness to address next-generational societal needs. Examples of such applied fields include precision agriculture, urban meteorology, aviation weather, and fire weather. In the latter, for instance, research opportunities continue to grow in the face of climate change, drought, and the associated devastating wildfires. For example, the United States Forest Service currently spends greater than 50% of its budget on fighting wildfires (USDA 2019). As the wildland-urban interface rapidly expands, there is a pronounced need to improve our understanding of, and the ability to forecast, the processes responsible for driving wildfires in an effort to mitigate losses to property and life.

Long-term goals

1. **Improve boundary layer parameterization**
   Naturally following from *short-term goal* item 1, we have a NWC community-wide opportunity to improve the methods by with boundary-layer processes are parameterized in Earth system models. This effort includes consideration of the full energy chain, from the subsurface, through the land surface and surface layer, and into the boundary layer. Some specific goals under this effort are to reduce model error and to develop ways to exploit increased resolution while maintaining skill. These efforts are especially important to developing the knowledge needed to downscale models in reasonable and physically relevant ways. As computational access increases, this need becomes increasingly noteworthy.

   There is a need for turbulence parameterizations that respond appropriately to both convective and stable boundary layers, while also being capable of representing high-shear environments related to severe convection environments. This is a challenge. It also is perplexing that NWP models operating on convection scales seem to do fairly well despite known deficiencies in boundary-layer parameterization. Perhaps model errors from elsewhere (e.g., microphysics) are on the same scale as errors associated with boundary-layer representation. It is unclear how such perceived importance may temper motivation to invest in boundary-layer parameterization development, but it is critical to models across scales and applications and will become more so as grid spacing continues its downward trend. Future boundary layer and turbulence schemes must be aware of how the scale of the area over which they are applied relates to the scale of the flow, scale of heterogeneities, and other features that may impact assumptions that are included within schemes. Observed data can be quite important in this effort, pointing again to the need for intentional and foundational collaboration between model and scheme developers and observational scientists.

2. **Land-atmosphere interaction**
   Understanding of land-atmosphere interactions is critical to many fields and applications such as climate modeling, seasonal-to-subseasonal prediction, agricultural weather forecasting, idealized simulations (lower boundary conditions), NWP, and parameterization. The present lack of updated and robust observed soil characteristics constrain land surface models. Without such observations, these models often rely on characteristics that were found in a particular region many decades ago, and whose potential errors are often larger than the magnitude of the values themselves. There is also a need for observations of fluxes and flux behavior. These observations can inform how various schemes handle situations that are not in line with assumptions used to derive Monin-Obukhov Similarity Theory, for instance (e.g., transition periods where fluxes and gradients may not be aligned). These observations and subsequent development work can support the implementation of rapid-response land-surface models that are more suitable for LES and other high-resolution simulations than traditional force-restore style models.

   These and other land-atmosphere interaction studies are also supportive of GeoCarb (e.g.,Moore III et al. 2018), which is a a unique collaboration seated at OU working with NASA and private industry partners. GeoCarb aims to monitor plant health and vegetation stress in the Americas and to elucidate the natural sources, sinks and exchange processes that are important to the cycles of carbon dioxide, carbon monoxide and methane in the atmosphere. In order to accomplish these goals, it is necessary to observe more than just constituent concentrations. Knowledge of boundary-layer processes is important for constraining and improvement of space-based constituent flux retrievals. Improved understanding of boundary-layer processes, boundary-layer and land-surface modeling, and the potential capability to estimate boundary-layer properties from space would all benefit this important mission.

3. **Role of aerosol in convection**
   The literature has hypothesized sometimes conflicting mechanisms to explain the role of aerosol in convection (e.g. Rosenfeld and Bell 2011; Yuter et al. 2013; Saide et al. 2015). Given our observational capability and location in the country, where convection and aerosol plumes are not uncommon, this is an area that—with specific and intentional collaboration—the NWC Community is well poised to explore. This focus is a natural extension of the convection initiation research discussed in *medium-term goals* item 1. We must identify and/or develop expertise within the NWC community in aerosol science. There also needs to be research and discussion about what is missing from our observation capabilities, specifically in terms of aerosol observation. Additionally, development of numerical tools that can represent aerosol processes is necessary. The recently funded DOE TRACER experiment may provide a dataset from which this effort can begin, but it will not be enough alone since sea breeze and urban effects may be conflated with aerosol processes.

4. **Supercell dynamics**
   In line with the traditional strengths of the NWC community, supercell dynamics should continue to be a focus of boundary-layer research efforts. There are many open questions in this area, such as supercell morphology and the role of internal or boundary-layer structures or boundaries in supercell evolution and longevity. Similar questions arise in the context of tornado potential. Outside of the Great Plains, there is great interest and need to develop understanding of the dynamics and

environmental controls of supercelluar storms embedded in broader convection systems. Tornadoes are, of course, not the only hazard to consider either. Boundary-layer research in the context of supercell dynamics may also help us understand severe wind potential.

5. **Non-canonical boundary layers**
   A significant portion of boundary-layer theory is derived from canonical dry, steady-state, horizontally homogeneous boundary layers. In order to meet the grand challenges and future needs of society, we need to focus on combining observations and simulations to study the many prevalent non-canonical evolving boundary layers. Examples include boundary layers associated with urban centers, coastal regions, clouds, fires, hurricanes, and more. By improving our understanding of these boundary layers, we will be able to account for effects from specific heterogeneities associated with the relevant phenomena and deliver more accurate forecasts for such important impacts as, e.g., pollution, fires, and hurricanes.

Looking to the future

Education, training, and recruitment

In order for any of the aforementioned efforts to be successful, we must strategically plan training and recruitment. As mentioned previously, the shift of many educational programs toward applied options is resulting in a shortage of well-trained and interested students entering the boundary-layer research community. We cannot neglect conscious efforts in retaining students and early-career scientists in these spaces. We must act together to address this. Here we describe the personnel needs we have in our community and some potential methods to fill them.

First and foremost we need content experts. These are people that understand and work with the boundary-layer theory and concepts of relevance *and* are willing to learn about observation and modeling state-of-the art. The pool of such candidates appears to be small. If organic recruitment is not feasible, this is a space where migration of other specialists is possible, though it should be carefully considered what type of specialists are proposed. We also need observation experts to drive and build observation frameworks. These individuals should have an intimate understanding of observation principles, data acquisition methods, and the current and future state of observation science and platforms. They should also have a basic understanding of numerical modeling needs and basic science questions in order to effectively lead observation efforts that support the broader community. On the other hand, we need modeling experts. These individuals should be well-versed and capable in numerical modeling and/or parameterization efforts and have a good understanding of the current and future progress of Earth system modeling. They should also have a basic understanding of observation capabilities and how to best use observed datasets to meet research goals. The final component we need in terms of personnel is operational buy-in. Given our close NWC community connections with operational entities and research-to-operation tasks, it will be highly beneficial to have folks with intimate knowledge of operational norms and needs to guide such efforts.

There are several methods that could support the growth of the above described personnel pool, both within the NWC community and the community at large (Fig. 2). First, collaborations are critical. This is a way to build pipelines of students and professionals from other institutions into the NWC community. It is also a way to support our own goals and broad community growth, which benefits us all. Continuing to publish and present at conferences and symposia is of course another way to build visibility in the broader community. Collaborative, cross-institution publications and presentations are additionally beneficial, as

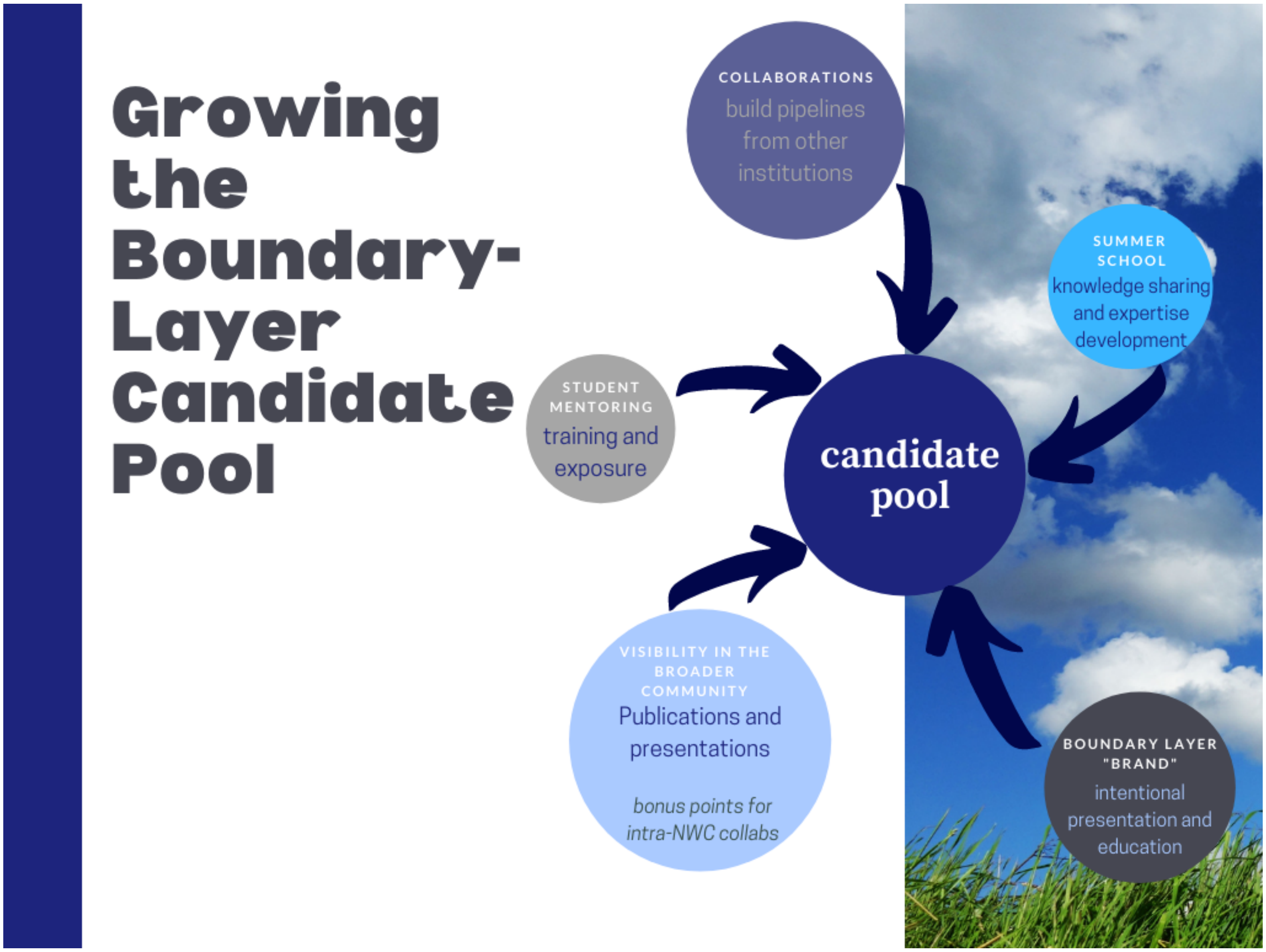

Figure 2. Visualization of the methods by which a candidate and talent pool can be built.

they market the real positive aspects of the relationships within the NWC community.

In this vein, we all share a responsibility to better represent the “brand" of boundary-layer meteorology. Those that are not well informed often think of boundary-layer meteorology and related topics as esoteric, non-applicable, engineering theory type fields. That is not what we are at the NWC. We can all work to improve this notion by purposely and intentionally presenting and informing the community of the breadth and applicability of our work in our conference talks, invited speaking events, and more. We have work to do here. Another way to build expertise in our own community and from outside collaborators may be a summer school concept, where experts, students, and/or early-career scientists are brought together to share knowledge and develop expertise.

Another critical facet which should be considered in education, training, and recruitment is diversity, inclusion, and equity in our education and research environments. One direct way to embark on an effort in building a more diverse workplace is to partner with NOAA Cooperative Science Centers such as the NOAA Center for Atmospheric Science and Meteorology, or NCAS-M, which connects students at minority serving institutions to research opportunities. For example, graduate fellows at NCAS-M must complete a NOAA Experiential Research and Training Opportunity, which is a 12-week research experience funded by the NCAS-M program at a NOAA facility like NSSL. There are other methods by which we can act to recruit and retain students and professionals from underrepresented communities into the NWC boundary-layer research network which we should identify and engage promptly.

Boundary-layer education at the SoM should also be considered, including coursework, research, and other learning opportunities. While encountered briefly in dynamics courses, and perhaps in a mesoscale course, there is little opportunity for boundary-layer education in the undergraduate meteorology curriculum. This could be addressed in several ways, including new elective courses, ungraded education opportunities (e.g., a special topics series that does not require enrollment), and through consistently available positive research mentoring opportunities. Actively mentoring students in the NWC community is very important and useful in this context. Non-faculty research staff could benefit from resources on developing positive research relationships with undergraduate assistants. At the graduate level, required so-called *core* courses do not cover boundary-layer topics except for the short section in Fundamentals of Atmospheric Science. This is something that should be evaluated, given the clear importance of boundary layer concepts to many fields and application in the NWC community. There are boundary-layer related electives offered, but the cadence and frequency of the offerings may be hindering student participation given prerequisite requirements. Development of new electives or special topics courses could address some of these issues, and could even be listed and taught in a way to include students and both undergraduate and graduate levels.

Several educational resources are desired by the community for students and for professionals. Many members of the NWC community could benefit from educational opportunities outside formal (i.e., enrolled and graded) classes. These opportunities could include training on project management, a shadowing program for proposal development or field campaign planning, and more. The concept of an 'educational' seminar series could offer opportunities for short educational lectures and demonstrations of concepts or tools relevant to the community while also offering the opportunity for individuals to build their teaching experience.

Community building

To grow a successful NWC boundary-layer research effort, the NWC boundary-layer research community must be built and supported. At present, the Boundary Layer Integrated Sensing and Simulation (BLISS) research group appears to be the best vehicle to move forward with community development. Through monthly group meetings and collaborative projects, the NWC community can grow and develop into a recognized leader in boundary-layer research. During focus group sessions, participants were asked to provide relevant ideas for research collaborations in our community, which were later organized into three main thematic zones (Fig. 3). The volume of information in this visualization shows how much capacity there is for innovative and impactful research within our local community.

Meetings alone are not enough to develop a functioning research community. This group can serve as a nexus for researchers interested in supporting student projects such as Capstone, Research Experience for Undergraduates, NOAA Experiential Research and Training Opportunity, and other such opportunities. There is a call for a unified repository of resources and tools available to the community including basic data manipulation scripts for NWC-generated datasets and examples of successful research and fellowship proposals. The need for standardization of data formatting and documentation, as well as calibration methods, was also identified, and is crucial to supporting modelers' use of observed datasets.

This community (e.g., the BLISS group) can also act together as a point of interface with external collab-

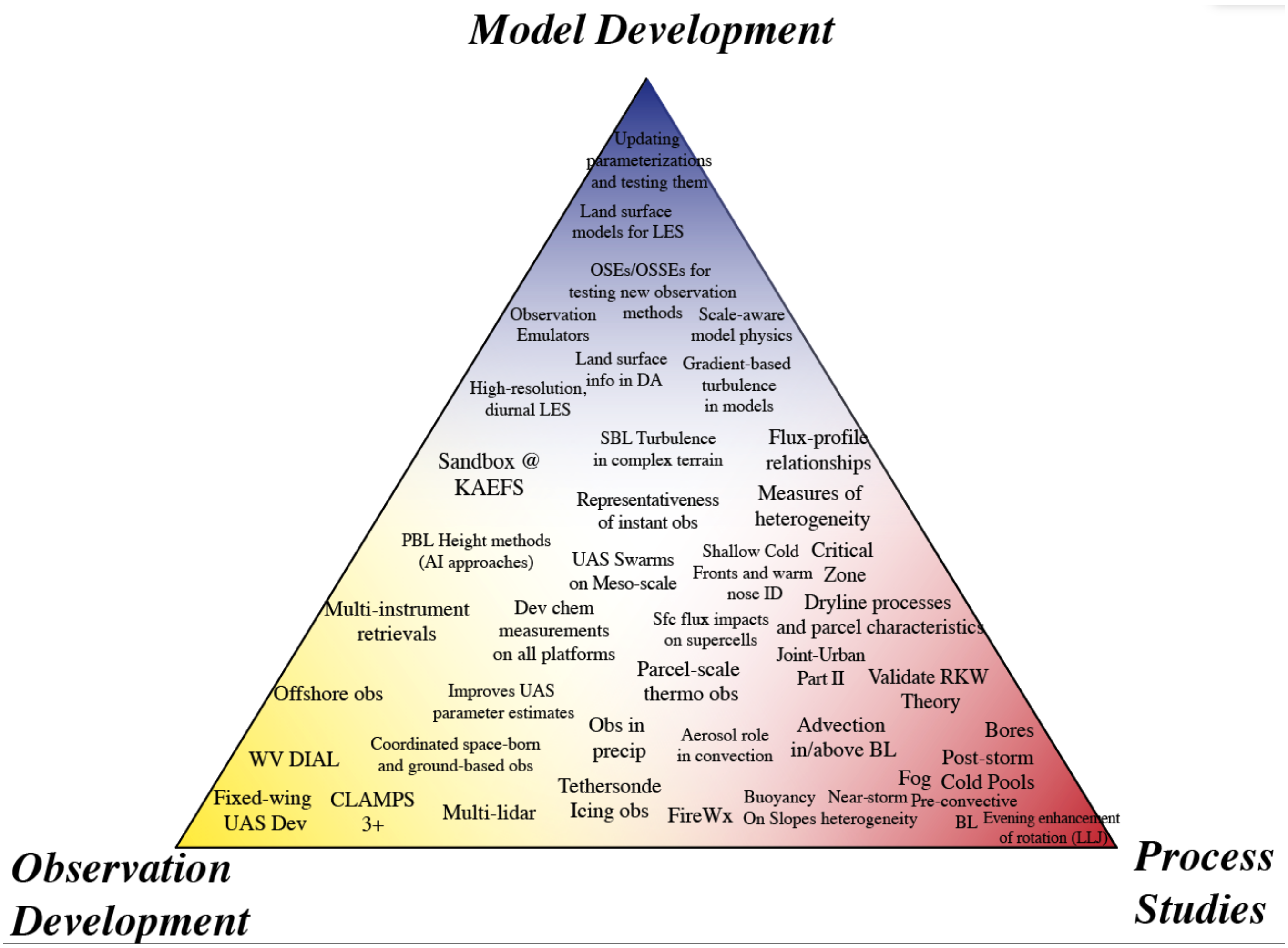

Figure 3. Collaborative research ideas organized in a ternary space between model development, observation development, and process studies.

orators and institutions. For example, several research topics of interest to the NWC boundary-layer research community have substantial overlap with the ongoing VORTEX-SE program. Through invited presentations and facilitated meetings, the BLISS group can be a vehicle for interactions with the VORTEX-SE program and community. Similar connections could be built with other programs and entities of relevance such as operational–to–quasi-operational modeling teams (e.g., WoFS, HRRR, NOAA UFS teams), NASA boundary-layer research groups, the GeoCarb team, and the Federal Aviation Administration.

Resources needed

For any community hoping to maintain a robust research program, some resources are necessary (Fig. 4). Of course funding and personnel needs are critical, but in this section we focus on other needed resources.

Computational resources continue to be needed to push forward with many boundary-layer research topics. At present, the OU Supercomputing Center for Education and Research (OSCER) is accessible to students and staff across the university. While suitable for many applications, the often long wait times typical of a widely shared resource can slow innovation and progress. Community-wide resources exist (e.g., NCAR Cheyenne), but access is limited to grantees and can be expensive. NOAA NSSL operates a

Figure 4. Word cloud made up of focus group participant feedback about the resources the NWC community needs to build up a boundary-layer research program.

supercomputing platform for its internal use, but this resources is not easily shared. The SoM is working to develop a virtual cluster solution, however it is not capable of addressing stretch needs for high-resolution modeling. This effort should continue to be supported. In general terms, more computing power is and will continue to be needed to address standing boundary-layer research problems. In addition to computing hardware, there is also a continued need for education for users (for students and professionals). This is currently left to most students or users to solve in their own time with little guidance. OSCER does offer many resources, but they have not always been well advertised or promoted within the NWC community. Another needed resource is engineering and technical support. When reviewing the successful model of the radar research efforts of decades past, it is clear that engineers and technicians were crucial to the success of scientists. A similar need is seen in the NWC boundary-layer research community. At NOAA NSSL, the Field Observation Facilities Support group acts to maintain the observation platforms owned and operated by NOAA NSSL. In collaborative spirit, this team has worked with NWC partners in the past. However, given the rapid expansion of NOAA NSSL observing capabilities, this partnership becomes harder to support. At the School of Meteorology, technicians and engineers appear to be supported by funding tied to specific instruments or specific grants. This structure makes it more difficult to collaborate on projects that need technician or engineering support. A base-funded pool for engineers and technicians supported by grant overhead and other revenue streams may be an avenue to explore, similar to the Advanced Radar Reseach Center (ARRC) model.

In addition to engineering and technician personnel, resources for those engaging in engineering and technical support roles (including scientists and graduate students) are needed. For example, a modern machine shop is not available for non-federal employees to access. There are no tools or benches for burgeoning atmospheric chemistry work. In terms of education, there is a need for overlapping course opportunities (e.g., instrumentation engineering. atmospheric chemistry). This solution requires either cross-listed courses or a change in the requirements for only METR courses counting toward meteorology degrees.

Measuring success

To evaluate and redirect the focus of a collaborative research community such as this one, it is important to develop measures for success as time progresses. Several methods to do so have been formulated.

First, it is appropriate and important to aggregate research outcomes and progress within the community. This can be done by collecting information and maintaining a record of peer-reviewed publications, conference presentations (especially recorded ones), and funded proposals. This data will allow for a periodic data-based review of the group's activity levels and collaborations.

In a broader sense, it is fruitful to complete a self-review of the NWC boundary-layer research community every 5 years. What has been accomplished? What has been learned? This is also an opportunity to retroactively review how new knowledge and research outcomes transition to operations or end users, which is particularly useful for outcomes of projects outside the clear research-to-operations pipeline. This is a unique opportunity this community has given our connections to operational entities within the NWC.

Recommended actions

In order to be successful in this effort to lead a new effort in boundary-layer meteorology on national and international scales, there are several possible actions we can take as the NWC community. Based on the state of boundary-layer research in the NWC community today, the relevant science goals we aim to pursue, and the new future we envision on the horizon, we recommend the following actions for consideration by those in decision-making positions:

1. Efforts to support and expand the observational capability of the NWC community should continue. As platforms are developed and introduced, the community should work to validate and evaluate them for application to our research foci. It is also important to continue to invest in the people and the efforts to design and innovate new observation concepts and methods to continue to act as community leaders in this space.

2. The NWC community must support existing and initiate new collaborations across institutions, agencies, and labs—both internally and externally. Internally, members of the NWC community should identify ways to collaborate in the immediate term, leveraging our combined strengths. This call to identify collaboration opportunities is especially relevant to NOAA NSSL, which should also find ways to collaborate with other OAR labs, such as the varied labs at the Earth Systems Research Laboratory.

3. Each entity should review its hiring and recruitment plans to make sure we invest in targeted talent. Our scientific expertise must expand soon. This includes hiring at all levels. For example, at NOAA NSSL the number of boundary-layer observation platforms is quickly outpacing the number of boundary-layer researchers. At the SoM, recent retirements and career transitions have shrunk the boundary layer focus of faculty research. A hire in the mesoscale boundary-layer interface would support this initiative, strengthen ties between the SoM and research partners, and maintain classical strengths for which the School is known. The current recruiting pool is somewhat small, so support is also needed across the NWC community for undergraduate students, graduate students, and postdoctoral researchers to help attract and develop talent.

4. We, as the NWC community invested in boundary-layer research, need to get the word out. This is not an area of expertise that is assumed to exist when people think about the National Weather Center. Additionally, there is often a lack of understanding about what boundary-layer research or topics really are in some parts of the broader atmospheric science community. Even locally, some scientists do not have a firm understanding of the work we do now and intend to do soon, or its value.

5. We need to get more researchers working with, and familiarized with, novel observation data (e.g., Doppler lidar, UAS) and modeling methods (e.g., LES). This can boost the number of researchers and the types of applications for which boundary-layer concepts become relevant.

6. We need to develop overlap and expand existing collaboration between modeling and observing teams.

7. We must find ways to exchange knowledge and develop new expertise, both in training and among currently involved scientists. A summer school may be one way to accomplish this goal. In addition to allowing existing knowledge to be shared with more members of the NWC community, this approach could also be an excellent external recruitment and exposure method.

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References

Cheong, B. L., D. J. Bodine, C. J. Fulton, S. M. Torres, T. Maruyama, and R. D. Palmer, 2017: SimRadar: A polarimetric radar time-series simulator for tornadic debris studies. *IEEE Trans. Geosci. Electron.*, **55 (5)**, 2858–2870, doi:10.1109/TGRS.2017.2655363.

Flora, M. L., P. S. Skinner, C. K. Potvin, A. E. Reinhart, T. A. Jones, N. Yussouf, and K. H. Knopfmeier, 2019: Object-Based Verification of Short-Term, Storm-Scale Probabilistic Mesocyclone Guidance from an Experimental Warn-on-Forecast System. *Weather and Forecasting*, **34 (6)**, 1721–1739, doi:10.1175/WAF-D-19-0094.1.

Gebauer, J. G., A. Shapiro, E. Fedorovich, and P. Klein, 2018: Convection Initiation Caused by Heterogeneous Low-Level Jets over the Great Plains. *Monthly Weather Review*, **146 (8)**, 2615–2637, doi:10.1175/MWR-D-18-0002.1.

Gibbs, J. A., E. Fedorovich, and A. M. Van Eijk, 2011: Evaluating Weather Research and Forecasting (WRF) model predictions of turbulent flow parameters in a dry convective boundary layer. *J. Appl. Meteor. Climatol.*, **50 (12)**, 2429–2444, doi:10.1175/2011jamc2661.1.

Laser, J., 2020: Evaluation of the Warn-on-Forecast System with Doppler Lidar and Mobile Radiosondes from TORUS2019. M.S. thesis, School of Meteorology, University of Oklahoma.

LeMone, M. A., et al., 2019: 100 Years of Progress in Boundary Layer Meteorology. *Meteorol. Monogr.*, **59**, 9.1–9.85, doi:10.1175/AMSMONOGRAPHS-D-18-0013.1.

Melnikov, V. M., R. J. Doviak, D. S. Zrnić, and D. J. Stensrud, 2011: Mapping Bragg Scatter with a Polarimetric WSR-88D. *J. Appl. Meteor. Climatol.*, **28 (10)**, 1273–1285, doi:10.1175/JTECH-D-10-05048.1.

Moninger, W. R., S. G. Benjamin, B. D. Jamison, T. W. Schlatter, T. L. Smith, and E. J. Szoke, 2010: Evaluation of Regional Aircraft Observations Using TAMDAR. *Wea. Forecasting*, **25 (2)**, 627–645, doi:10.1175/2009WAF2222321.1.

Moore III, B., et al., 2018: The potential of the geostationary carbon cycle observatory (geocarb) to provide multi-scale constraints on the carbon cycle in the americas. *Frontiers Environ. Sci.*, **6**, 109, doi:10.3389/fenvs.2018.00109.

National Academies of Sciences, Engineering, and Medicine, Engineering, and Medicine, 2018: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. The National Academies Press, Washington, DC.

National Research Council, 2009: *Observing Weather and Climate from the Ground up: A Nationwide Network of Networks*. The National Academies Press, Washington, DC, doi:10.17226/12540.

National Research Council, 2010: *Informing an Effective Response to Climate Change*. The National Academies Press, Washington, DC, doi:10.17226/12784.

Reif, D. W. and H. B. Bluestein, 2018: Initiation Mechanisms of Nocturnal Convection without Nearby Surface Boundaries over the Central and Southern Great Plains during the Warm Season. *Mon. Wea. Rev.*, **146 (9)**, 3053–3078, doi:10.1175/MWR-D-18-0040.1.

Rosenfeld, D. and T. L. Bell, 2011: Why do tornados and hailstorms rest on weekends? *J. Geophys. Res. Atmos.*, **116 (D20)**, doi:10.1029/2011JD016214.

Saide, P. E., et al., 2015: Central American biomass burning smoke can increase tornado severity in the U.S. *Geophys. Res. Lett.*, **42 (3)**, 956–965, doi:10.1002/2014GL062826.

Shapiro, A. and E. Fedorovich, 2009: Nocturnal low-level jet over a shallow slope. *Acta Geophys.*, **57 (4)**, 950–980, doi:10.2478/s11600-009-0026-5.

Shapiro, A., E. Fedorovich, and J. G. Gebauer, 2018: Mesoscale Ascent in Nocturnal Low-Level Jets. *Journal of the Atmospheric Sciences*, **75 (5)**, 1403–1427, doi:10.1175/JAS-D-17-0279.1.

Shin, H. H. and J. Dudhia, 2016: Evaluation of PBL Parameterizations in WRF at Subkilometer Grid Spacings: Turbulence Statistics in the Dry Convective Boundary Layer. *Mon. Wea. Rev.*, **144 (3)**, 1161–1177, doi:10.1175/MWR-D-15-0208.1.

Smith, E. N., J. G. Gebauer, P. M. Klein, E. Fedorovich, and J. A. Gibbs, 2019: The Great Plains Low-Level Jet during PECAN: Observed and Simulated Characteristics. *Mon. Wea. Rev.*, **147 (6)**, 1845–1869, doi:10.1175/MWR-D-18-0293.1.

Stith, J. L., et al., 2019: 100 Years of Progress in Atmospheric Observing Systems. *Meteorol. Monogr.*, **59**, 2.1–2.55, doi:10.1175/AMSMONOGRAPHS-D-18-0006.1.

USDA, 2019: Wildland Fire. U.S. Department of Agriculture, accessed 04 September 2020, https://www.usda.gov/topics/disaster/wildland-fire.

Wulfmeyer, V., et al., 2015: A review of the remote sensing of lower tropospheric thermodynamic profiles and its indispensable role for the understanding and the simulation of water and energy cycles. *Rev. Geophys.*, **53 (3)**, 819–895, doi:10.1002/2014RG000476.

Wyngaard, J. C., 2004: Toward numerical modeling in the "terra incognita". *J. Atmos. Sci.*, **61 (14)**, 1816–1826, doi:10.1175/1520-0469(2004)061<1816:TNMITT>2.0.CO;2.

Yuter, S. E., M. A. Miller, M. D. Parker, P. M. Markowski, Y. Richardson, H. Brooks, and J. M. Straka, 2013: Comment on "Why do tornados and hailstorms rest on weekends?" by D. Rosenfeld and T. Bell. *J. Geophys. Res. Atmos.*, **118 (13)**, 7332–7338, doi:10.1002/jgrd.50526.

Zhang, Y., D. Li, Z. Lin, J. A. Santanello, and Z. Gao, 2019: Development and Evaluation of a Long-Term Data Record of Planetary Boundary Layer Profiles From Aircraft Meteorological Reports. *J. Geophys. Res. Atmos.*, **124 (4)**, 2008–2030, doi:10.1029/2018JD029529.