Scientific Challenges and Opportunities in the NASA Weather Focus Area

Xubin Zeng[1], Steve Ackerman[2], Robert D. Ferraro[3], John J. Murray[4],
Steven Pawson[5], Carolyn Reynolds[6], Joao Teixeira[3]

[1]University of Arizona
[2]University of Wisconsin-Madison
[3]Jet Propulsion Laboratory
[4]NASA LaRC
[5]NASA GSFC
[6]NRL-Monterey

1. Introduction

Weather covers atmospheric phenomena with time scales from minutes to about two weeks and with spatial scales from local to global. It also covers the sub-seasonal to seasonal time scale that bridges weather with climate.

Weather matters for life, health, safety, property, and economic prosperity. Weather forecasts provide information that people and organizations can use to enhance these societal benefits and to reduce weather-related losses. Despite its importance, however, in the past decade, climate and earth system research has received much more attention than weather research in the U.S.

As input for the NASA Earth Science Weather Focus Area advanced planning, a community workshop was held in April 2015 to produce a report examining the scientific challenges and opportunities in weather research. About 70 invited participants attended this workshop, including individuals from government agencies, academia, the private sector, and other national and international organizations. The Workshop mixed broad review talks, in-depth research discussions, and more than 40 one-slide presentations on Day 1, followed by breakout and plenary discussions on Day 2. The full Report (including the list of participants) is available at http://science.nasa.gov/earth-science/focus-areas/earth-weather/.

This White Paper is based on the Workshop Report. It addresses all three questions in the Request (science questions; their timeliness and readiness; and value of space-based measurements) in Sections 2 and 3. It also covers all four issues (new investments versus existing measurements; space-based versus other measurements; benefits; and science community involvement) in Sections 1, 3, and 4.

Furthermore, Section 3 emphasizes the use of Observing System Simulation Experiments (OSSEs) as a tool in measurement-related impacts and cost benefits analysis, while Section 4 emphasizes the importance of modeling, data assimilation (DA), and computing for applications of space-based measurements. The science questions and recommendations below represent a snapshot of the community's views on selected topics most relevant to NASA's observations, research, and application portfolios, rather than a comprehensive review of all weather-related topics.

2. Science questions

Using NASA's capabilities in observations, modeling and DA systems, instrument platforms, and computing facilities, a variety of fundamental science questions can be addressed in the Weather Focus Area. For weather prediction and predictability:

- What are the scientific advances and observations needed to expand the useful range of weather forecasting from 0-2 weeks to 0-4 weeks?
- What are the scientific advances and observations needed to extend and improve prediction of extreme weather events (e.g., the snow events of the U.S. East Coast in 2015, the Texas floods in 2015, hurricane Sandy in 2012, and the tornado outbreak on 25-28 April 2011)?

For convection and precipitation:

- How do convective-scale and large-scale circulations interact?
- What determines the mesoscale organization, internal structure and dynamics, and life cycle of convective systems?
- What modulates the rate at which convective storms intensify to produce severe weather, tornadic storms, lightning, and other hazards?
- What processes and interactions control the type, onset, rate, and accumulation of precipitation?

For planetary boundary layer and land/ocean surface processes:

- How does moist convection interact with the boundary layer and the surface?
- What are the fundamental mechanisms controlling boundary layer clouds?
- How can we unify the parameterization of moist and dry turbulence and convection as well as clear air turbulence?

For clouds and radiation:

- What processes determine cloud microphysical properties (ice clouds in particular) and their connections to aerosols and precipitation?
- What is the spatio-temporal structure of cloud systems?

Complete answers to these questions require a broad range of investments, from making new observations designed to focus on processes at work in various parts of the Earth system, through systematic modeling studies designed to examine processes at the micro- and macro-scale, as well as in the context of the global weather.

Further, as new components of the global observing system become feasible, quantitative studies of their impacts and cost benefits need to be made, such as through the use of OSSEs. Seeking answers to these questions led to seven recommendations below.

3. Measurements and OSSEs

The transitions from investment in new technologies to building new instruments, and to developing new missions are an essential part of developing new observations. Bringing new missions to fruition requires methods to estimate the success of the technological development and the likely cost effectiveness of the observations. OSSEs provide a tool to assess the impacts of new observations, in the context of the existing observing system, and hence contribute to estimating the value of potential new missions.

Recommendation on OSSEs: The Weather Focus Area should take ownership of a NASA Earth Science OSSE capability for assessing the impact of measurements and measurement systems on the ability to answer weather and related science questions. In this way, mission systems trade studies can be evaluated against science impact and mission cost and technology development. Serious consideration should be given to increasing NASA and NOAA interagency collaborations, including evolving the current shared OSSE elements into a common unified infrastructure.

Recommendation on wind measurements: Global measurements of the spatio-temporal (four-dimensional) evolution of large-scale horizontal wind vectors are urgently needed. It is important to avoid all or nothing strategies for the three-dimensional wind vector measurements, as important progress is possible with less than comprehensive observing strategies. Some additional tradeoff studies may still be needed to design the most cost-effective strategy for wind measurements (based on lidar, radar, and atmospheric motion vectors) from satellites and airborne flights.

Recommendation on temperature and humidity measurements: Continuous investment in temperature and humidity measurements is needed, particularly focusing on higher spatial and temporal resolution, and synergistic measurements involving multiple instruments, different platforms (geosynchronous, low earth orbit, and airborne), and different types of satellites (including small-sat and cubesat). Better measurements from space of the temperature, water vapor, and wind in the boundary layer are needed, in particular to estimate more accurately from space ocean/land surface turbulent fluxes that are closely coupled to boundary layer and convection processes.

Recommendation on cloud and precipitation measurements: Continuous investment in cloud and precipitation measurements is needed, particularly focusing on higher spatial and temporal resolution, and synergistic measurements involving multiple instruments (e.g., radar, radiometer, and lidar observations), different platforms (geosynchronous, low earth orbit, and airborne), and different types of satellites (including small-sat and cubesat). Observational estimates of the vertical velocity within convective systems are particularly important in this context.

New instrument technology maturity for making all of these measurements was also examined during the workshop. A key finding was that “The issue is not the ability to make the measurement. It is the question of how comprehensive a measurement is needed to have impact on science and forecast skill.” There are tradeoffs in each measurement system that need to be examined in order to get the best cost/benefit to the science.

4. Modeling, data assimilation, and computing

Modeling, DA, and high-end computing are an integral part of the NASA Weather Focus Area. A sustained modeling and assimilation framework would also promote the transition of suitable research-type observations into operational systems at NOAA.

Recommendation on modeling: Global high-resolution modeling (convective permitting with grid sizes of 1-5 km) should be pursued as an essential contribution to the broad national and international modeling activities and to NASA mission planning. This involves the research support of dynamic core development, physical processes, software engineering, and high-performance computing. Research on, and development of, other high-resolution models (e.g. mesoscale, cloud resolving and large-eddy simulation models) need to be pursued in parallel.

Recommendation on DA: NASA should collaborate closely with operational and research centers and support research on cutting-edge assimilation issues such as: hybrid ensemble-based 4-dimensional variational DA, all-sky radiance assimilation, assimilation of properties related to clouds and radiation, land surface emissivity, coupled DA of the atmosphere-ocean-land-ice system, and DA evaluation metrics.

Recommendation on computing: NASA should match supercomputing capability and capacity with continued development of a high-resolution modeling capability directed at using all observations to their fullest extent for weather prediction and for planning for new global observations. Enhanced data-distribution techniques (e.g., storage proximal analytics) are needed for data access and discovery.

These science questions and recommendations require NASA to work closely with other agencies, academia, the private sector, and international partners. At the same time, NASA has a unique role in weather research (as reflected by the above science questions and recommendations) through the Weather Focus Area, relative to its partners. NASA is the only agency in the U.S. with the capability to develop new technologies and satellite missions for the above measurements. This also requires NASA's leadership role in OSSEs.

While modeling, DA, and computing efforts are also covered by NOAA, NSF, DOD, and the private sector, NASA's unique role is to focus on modeling and DA that will help NASA mission planning and assimilation of new measurements. In this way, NASA will accelerate the transition of technology, instruments, observational data, modeling, and DA to operations (e.g., at NOAA) and applications. This also requires NASA's sustained investment in supercomputing capability and capacity.

Finally, while NOAA, NSF, DOD, and, to a lesser extent, the private sector, perform weather research, NASA's unique role is to use its capabilities in instrument technology development and new mission conceptualization to pioneer the next generation of instrument platforms, observations, and modeling and DA systems to address these science questions.