National Aeronautics and Space Administration

8 July 2015

Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area

On the cover: The natural-color image of Hurricane Blanca off the coast of Mexico from MODIS on NASA's Aqua satellite at 1:35 p.m. local time on 3 June 2015. The storm is the earliest second hurricane on record for the eastern Pacific Ocean. Source: *http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=85983&src=ve*

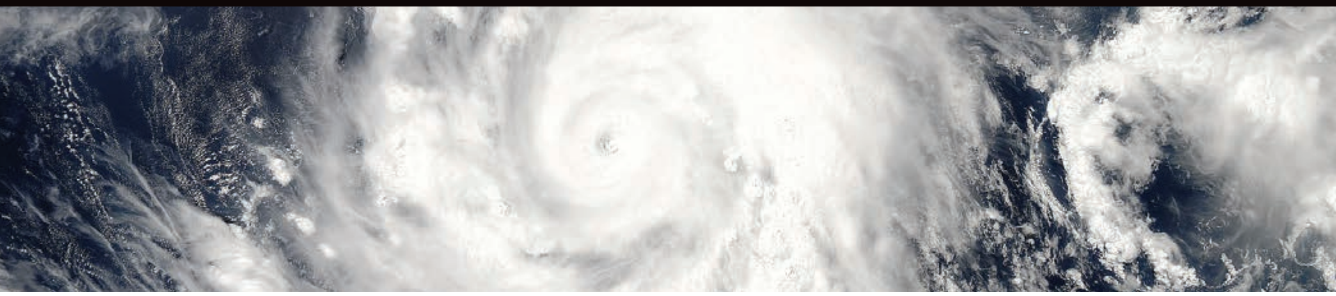
8 July 2015

Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area

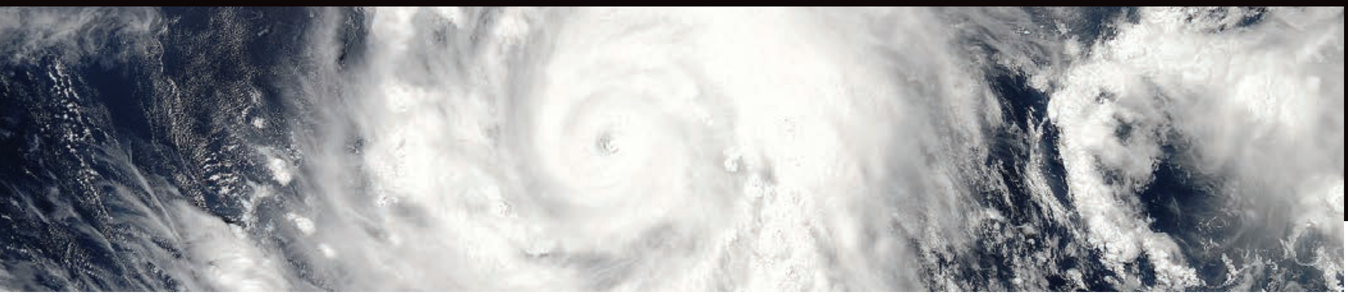
Xubin Zeng[1], Steve Ackerman[2], Robert D. Ferraro[3], John J. Murray[4], Steven Pawson[5], Carolyn Reynolds[6], and Joao Teixeira[3]

1. University of Arizona • 2. University of Wisconsin • 3. NASA JPL • 4. NASA LaRC • 5. NASA GSFC • 6. NRL

Contents



Executive Summary



NASA'S EARTH SCIENCE RESEARCH includes six focus areas: Atmospheric Composition, Weather, Climate Variability and Change, Water and Energy Cycle, Carbon Cycle and Ecosystems, and Earth Surface and Interior. 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 (S2S) time scale that bridges weather with climate. The research programs of the Weather Focus Area were developed nearly ten years ago. With new NASA capabilities, scientific progress made in the past decade, and the current budget landscape in mind, a community Workshop was held on 7–9 April 2015 to produce this Workshop Report to serve as part of the advanced planning process for the NASA Weather Focus Area.

About 70 invited participants representing a cross section of the weather research community attended this Workshop, including individuals from government agencies, academia, private sector, international, and other organizations. The Workshop mixed broad review talks, in-depth research discussions, and more than 40 one-slide presentations on Day 1, followed by breakout discussions on Day 2. The first breakout session focused on three themes: convection and precipitation; planetary boundary layer and ocean/land surface; and clouds and radiation. The second breakout session focused on three different themes: science questions; new instruments/technology; and modeling/data assimilation.

Using NASA's capabilities in observations, modeling and data assimilation 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, the questions include:

- 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, the questions include:

- 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 (of all types) 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, the questions include:

- 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, the questions include:

- 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 Observing System Simulation Experiments (OSSEs). Seeking answers to these questions led to four recommendations for measurements and OSSEs, and three recommendations for modeling, data assimilation (DA), and computing. **These recommendations and the above science questions represent a snapshot of the community's views on selected topics, rather than a comprehensive review of all weather-related topics.**

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 done against impact and cost for satellite missions 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 trade 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). Particularly relevant to these measurements is the estimate of the vertical velocity.

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, 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) also need to be pursued in parallel.

Recommendation on data assimilation: NASA should collaborate closely with operational and research centers and support research on cutting-edge assimilation issues such as: hybrid ensemble-based 4D-Var, 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 the supercomputing capability and capacity with the growth in a sustained, high-resolution modeling capability directed at using all observations to their fullest extent in weather prediction and at planning for new global observations. Enhanced data-distribution techniques (e.g., storage proximal analytics) are also needed for data access and discovery.

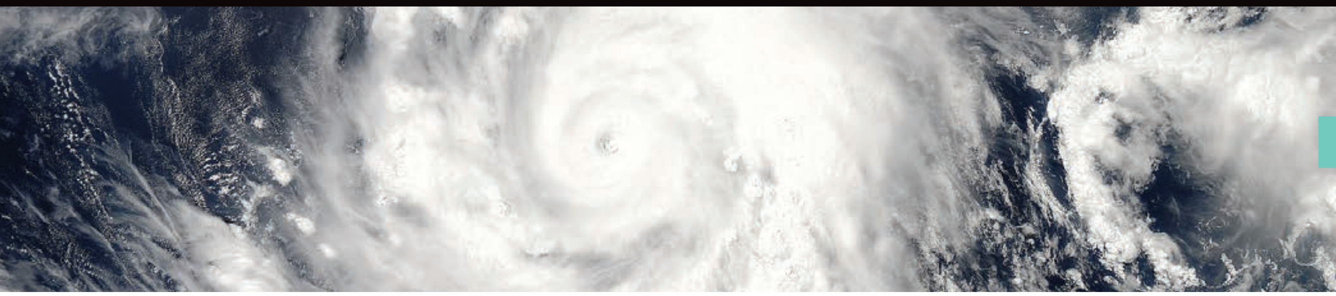
These science questions and recommendations require NASA to work closely with other agencies, academia, the private sector, and international partners, including the leverage of existing partnerships such as the National Earth System Prediction Capability (ESPC) and Joint Center for Satellite Data Assimilation (JCSDA) as well as joint satellite missions with 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, data assimilation, and computing efforts are also covered by NOAA, NSF, DOD, and the private sector, NASA's unique role is to focus on modeling and data assimilation 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 data assimilation 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, do 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 data assimilation systems to address these science questions.

Introduction



1

NASA'S EARTH SCIENCE RESEARCH includes six focus areas: Atmospheric Composition, Weather, Climate Variability and Change, Water and Energy Cycle, Carbon Cycle and Ecosystems, and Earth Surface and Interior. It is conducted in four major areas: research and analysis, satellite missions, applied sciences, and enabling capabilities (e.g., data and information systems, high-end computing, airborne science, and technology development). The four guiding principles of the NASA Weather Focus Area are:

- Weather systems include not only the dynamics of the atmosphere but also interaction with the oceans and land.
- Weather includes local or microphysical processes that range in temporal scales from minutes to two weeks.
- Weather as a societal benefit area is strongly coupled to climate, the water cycle, and energy.
- In addition to performing fundamental Earth science research for weather, NASA plays a very important role in the introduction of new technologies for use by operational weather agencies.

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 (S2S) time scale that bridges weather with climate. The current research programs of the Weather Focus Area were developed nearly ten years ago. With the enhanced observational and modeling capabilities that NASA has developed, advances in scientific understanding in the past decade, and the current budget constraints, this Workshop serves as part of the advanced planning process for the NASA Weather Focus Area.

The **purpose** of the Workshop was to gather community leaders to identify the most challenging scientific research and development topics that can be uniquely addressed by the Weather Focus Area. This spans the use of NASA's satellite, airborne, and surface observations, computational modeling and data assimilation systems, instrument (airborne and satellite) platforms, and high-end computing facilities. The emphasis was on the use of new kinds of observational, modeling, computational capabilities that are available at present or planned for the future. The specific questions addressed were:

- What are the main scientific challenges in weather research (e.g., in fundamental understanding, model development, data assimilation, and research to operation or application transitions)?
- What are the main opportunities in weather research using new satellite observations and suborbital field campaigns?
- How can we leverage available NASA observations as well as new observing systems for weather research?
- What measurements are urgently needed and can be made through future NASA missions?
- What is NASA's unique role in weather research through the Weather Focus Area, relative to NOAA, NSF, and DOD?

The Workshop was held 7–9 April 2015 to address these questions. The Organizing Committee consisted of Xubin Zeng (Chair; U. Arizona), Carolyn Reynolds (Co-Chair; NRL), Steve Ackerman (U. Wisconsin), Steven Pawson (NASA/GSFC), and Joao Teixeira (NASA/JPL). The Advising Committee consisted of Tsengdar J. Lee (Chair; NASA Headquarters), Robert D. Ferraro (NASA/JPL), and John J. Murray (NASA/LaRC). **Appendix A** provides the Workshop program, including the time, place, and Web site, while **Appendix B** gives the list of participants. The Acronym List in this report is provided in **Appendix C**.

Although the initial intent was to invite about 50 participants, with appropriate balance and diversity among organizations (e.g., government, educational, industrial) and disciplines (e.g., modeling and data analysis, observations, technology), and diversities, the enthusiasm in the community pushed the number of invitees to about 70. These participants cover:

- **Government agencies:** NASA (HQ, JPL, GSFC, LaRC, MSFC), NOAA (NWS, OAR, NESDIS), DOD (Navy, NRL), NSF, FAA, OFCM, JCSDA
- **Academia:** U. Wisconsin, U. Arizona, NCAR, Colorado St. U., U. Oklahoma, Penn St. U., U. Colorado, U. Miami, George Mason U., U. Maryland, MIT, U. Georgia
- **Private sector:** ERT, Raytheon, Northrop Grumman, BAE, Ball Aerospace
- **International:** ECMWF
- **Others:** National Academies BASC, AMS

The primary **outcome** is this Workshop Report that will be submitted to the NASA Weather Focus Area and shared with the community. This report is intended to be used to help identify research opportunities in the NASA Weather Focus Area. It also represents a valuable input to other NASA programs (e.g., technology development). Finally, it could be a useful input to the NRC Earth Science Decadal Survey.

The first day of the Workshop mixed broad review talks, in-depth research discussions, and more than 40 one-slide presentations. A brief summary of these presentations is provided in **Section 2**, with the invited talks summarized in **Section 2.1** and the one-slide presentations in **Section 2.2**. These talks set the stage for two sets of three breakout discussion sessions on the second day. The first session (**Section 3**) focused on three themes: convection and precipitation (and its discussions and findings are summarized in **Section**

3.1), PBL/ocean surface/land surface (**Section 3.2**), and clouds and radiation (**Section 3.3**). Each theme had a near-equal number of participants assigned to it by the organizers in a quasi-random fashion to ensure a good mix of people with different backgrounds. The second breakout session (**Section 4**) focused on three different themes: science questions [including (weather-to-climate transition) sub-seasonal to seasonal issues] (**Section 4.1**), new instruments/technology (including emerging and underutilized existing instruments) (**Section 4.2**), and modeling/data assimilation (**Section 4.3**). Participants chose the themes to attend themselves, but the number of participants for each theme turned out to be approximately equal despite the self-selection process. Based on these discussions, the overall findings and recommendations are provided in **Section 5**.

The Committee finished the report on 14 June 2015 and e-mailed it to all Workshop participants for comments by 21 June 2015. The committee then finalized the report.

Invited and Contributed One-Slide Presentations

2

AFTER TSENGDAR LEE (NASA WEATHER Focus Area Lead) welcomed the participants, Xubin Zeng (Committee Chair) gave the opening remarks, summarizing the diversity of participants, community enthusiasm, and the long history of NASA-NOAA collaboration. He also discussed the purpose and outcomes of this Workshop, as well as the focus on actionable and NASA-relevant topics and suggestions.

2.1 Brief Summary of Invited Talks

In **Session 1**, Jack Kaye overviewed the current status and near-future plans of the NASA Earth Science Research Division. NASA research and missions are related to weather and extreme weather events. He emphasized the close connection of the Weather Focus Area with most of the other Focus Areas. He also emphasized that, unlike other focus areas, the Weather Focus Area is where NASA does not have a clear leadership role and there is a need for the Weather Focus Area to collaborate with operational agencies (particularly NOAA) on research and operational sensor intercomparisons, and with other space agencies. Nevertheless, NASA does have significant capability and capacity. Looking forward, there will be continued interest in providing the weather research and development community critical tools such as suborbital enhanced temporal sampling, smaller platforms, instrument development, satellite observations, computing, modeling and data assimilation capabilities, and moving beyond large LEO platforms. There will be continued effort in working with other space agencies (e.g., ESA's Atmospheric Dynamics Mission Aeolus), and a continued push to seamless weather-climate prediction. In the current budget environment particularly, it will be important to prioritize our ambitions and to collaborate with partners to identify the role of observations in extending prediction beyond current weather timescales. In addition, data to support high-resolution models (1–10 km at high temporal frequency) will be needed.

William Lapenta overviewed weather research in the United States with a focus on challenges and research to operation (R2O) transitions. He emphasized that the NWS strategy for Weather-Ready Nation involves the entire U.S. weather enterprise working together to achieve far-reaching national preparedness for weather events, and operational prediction is what makes NWS unique and indispensable. He also identified four strategic areas in research and development: 3–4 weeks forecasts (closing the gap between weather and climate), extending lead time for high impact events, incorporating a full Earth system science approach, and strategically transitioning from research into operations. The role of other federal agencies (e.g., NASA), the academic community, and the private sector in the NWS R2O initiative was also identified.

David McCarren provided the interagency perspective from OFCM and emphasized the R2O (from NASA research missions to NOAA operational missions) challenges. For instance, the duration of a NASA mission may not be long enough to determine the operational value and to implement operationally. He also emphasized the connection of weather with climate. Finally, he identified the major challenges in weather research, such as the high resolution Earth system prediction with coupled data assimilation and next generation of affordable and supporting observation systems.

Amanda Staudt has reviewed weather-related reports from the National Academies over the past 10 years. Common themes from these reports include: meeting user needs (e.g., hazards, high-impact weather, and urban meteorology), engaging the full enterprise (e.g., partnerships, R2O, and O2R), and longer time horizons and linkages (e.g., sub-seasonal to seasonal variability, linkages of weather conditions with other climate variables such as sea ice). She also briefly mentioned the criteria for future missions in the 2nd NRC Decadal Survey in Earth Science and Applications from Space, including science priorities, implementation costs, new technologies and platforms, interagency partnerships, international partners, and in situ and other complementary programs.

In **Session 2,** presentations discussed the challenges of three broad topics that NASA's unique capabilities can address: modeling (Joao Teixeira and Bill Putman), data assimilation (Ron Gelaro), and satellite observations (Steve English). Teixeira provided a detailed overview of the physical parameterizations in weather prediction models, including parameterizations for radiation, turbulence, convection, and surface fluxes. He noted the complexities of developing good and physically realistic parameterizations while clearly demonstrating their essential contributions to weather forecasting. He noted that to improve parameterizations in numerical weather prediction models requires much higher resolution observations of the atmospheric profiles of temperature, humidity, water (liquid and ice phase), and precipitation. He also stressed that future satellite missions need to include experts in weather modeling and data assimilation early in the mission planning.

Putman discussed high-resolution global modeling with the GEOS-5 model. He discussed the science and computing requirements of going to high resolution modeling and provided several examples of GEOS-5 simulations and their comparisons to observed conditions. He noted the ability of these model upgrades to better simulate convective systems, concluding that high resolution OSSEs can be used to evaluate observing system strategies.

Gelaro's presentation discussed the status and challenges of data assimilation and how to blend the model fields with observations. Satellite observations provide information, usually in the form of radiances, about the actual atmosphere but are often irregular in space and time. In contrast, models provide regular and physically consistent information about the system, though prone to systematic errors. Accurate estimates of background and observation error statistics are essential for combining information optimally, and he provided a review of how this can be accomplished. He also gave an interesting example of the observations that were assimilated in the GEOS-5 atmospheric data assimilation system over a typical six-hour assimilation window.

The session ended with English discussing the opportunities, challenges, and needs for satellite observations in weather forecasting. Weather forecasting is an initial value problem and satellite observations help provide the initial conditions needed to solve that problem on a routine basis. Spatial resolutions of about 1 km and consistent temporal resolution along with better characterized uncertainties in the observations are what are needed in new satellite observations. He noted that NASA missions have been essential to weather research and progress in skill of operational forecasts and, where possible, the community should be thinking of the role of research missions as a prototype for future operational missions and plan accordingly.

Session 3 of the Workshop included four presentations. The first two gave perspectives on the role of field campaigns, from NASA and from NSF. These were followed by a review of technological investments from NASA/ESTO. Finally, the role of high-performance computing in NASA's Earth Science Mission was discussed.

Gerald Heymsfeld gave an overview of NASA's weather-related field campaigns, emphasizing NASA's strengths in providing airborne platforms, airborne sensors, and associated ground-based radar assets. Investments in platforms include high- and medium-altitude aircraft, which provide unique opportunities for testing new remote sensing instruments and techniques. The airborne sensors include a variety of lidars, radars, radiometers, and sounders, which are used to provide observations in and around major weather events, including hurricanes. The observing program has developed since the mid-1980s, with increasing capabilities that now utilize unmanned aircraft (Global Hawks) for observations over vast areas of the globe. The airborne assets are complemented by ground- and ship-based measurements, facilitating studies of the genesis and evolution of selected weather events, as well as coordinated missions to provide ground truth for space-based missions, such as GPM.

NSF's major airborne assets, supported through NCAR/EOL were presented by Vanda Grubišić. This is a substantial investment that has generally increased in the 1995–2015 time frame, typically supporting one-to-two weather-related campaigns each year. These missions are often performed in conjunction with other agencies, including the use of a comprehensive drop-sonde system (AVAPS) on NASA aircraft. Several missions were described in detail, including the use of NCAR's GV aircraft, equipped with the HIAPER cloud radar, to study the structure of a rapidly developing Nor'Easter in February 2015. Future campaigns are anticipated, including interagency efforts to study severe weather systems.

NASA/ESTO's investments in instrument (and information) technology, relevant to weather, were discussed by Parminder Ghuman. The investigations span the development of technologies that provide measurements to determine wind, clouds and precipitation, and temperature and moisture. These include different types of wind estimation: active sensors (lidar) for profiles; scatterometers for ocean-surface winds; and constellations of small-satellites (hyperspectral infrared information used to determine atmospheric motion vectors). Various types of radar for investigations of clouds and precipitation are also under investigation. Radiometer technologies would provide information on global moisture distributions. In these cases, developments of small-satellite technologies are a key investment. Various studies of water vapor profiling are also under investigation, ranging from radiometers to active lidar sensors. Other ESTO investments are in information technology, to enhance the use of computing technologies in weather research.

Dan Duffy presented the current status and future prospects for NASA's High-Performance Computing. NASA's current computing capacity can support the use of global models with grid sizes of around 20 km to make five-day forecasts every six hours. Advances to the 3–10 km scale may be anticipated over the next few years, yet the computation requirement of about 300,000 cores to run timely forecasts begins to exceed availability. Our ability to run cloud-resolving models over the globe is limited by both computing core availability and the power that would be required by such a machine, if it existed. New computing technologies will be needed for such problems. The limitations of web and data services were also noted: the need to build accessible data archives, with analytic services, was emphasized.

2.2 Brief Summary of Single-Slide Presentations

Each attendee was asked to provide one slide, addressing the question "What is a major scientific challenge in weather research that should and can be uniquely addressed by the NASA Weather Focus Area?" Forty-six participants gave very brief (two minute) descriptions of their slide over the course of a 90-minute session. While this format obviously did not allow for in-depth discussion, it did allow for a broad canvassing of the concerns and priorities of the attendees.

The organization with the largest representation in the group was NASA (14 slides), followed by 13 slides from academic representatives, 6 slides from private sector representatives, 4 slides from NOAA representatives, and 2 slides from NCAR representatives. One slide each was presented by representatives from a diverse group of organizations and interagency committees including the NRL, ECMWF, NSF, FAA, OFCM, JCSDA, and the AMS Forecast Improvement Group.

In order to summarize common themes and concerns of the attendees, references to different phenomena, observations, and modeling system capabilities were tabulated from the slides. The urgently needed observations that representatives mentioned most frequently were high (temporal and spatial) resolution wind profiles (explicitly mentioned in 13 slides) and high resolution temperature and water vapor profiles (mentioned 13 times). Ocean and land observations that would facilitate coupled data assimilation and forecasting were highlighted six times each, illustrating the importance of integrating different components of the Earth system in understanding and forecasting weather. The importance of precipitation observations was mentioned five times. The importance of observations over oceans, water vapor distributions, clouds, lightning, microphysical processes, and observations at aircraft cruise altitude were all mentioned at least once.

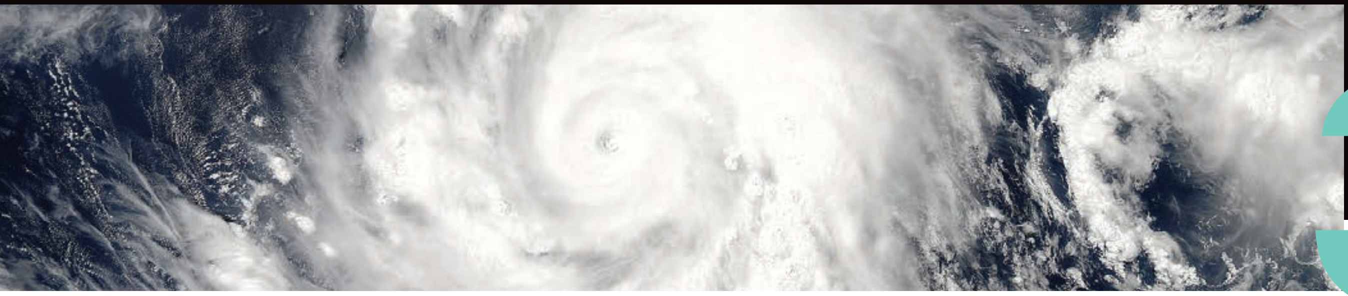
The phenomena of concern or specific forecast type varied widely, as might be expected from such a diverse group and broad subject. Extreme events were mentioned seven times, with tropical cyclone structure and intensity, tropical-extratropical interactions, extreme precipitation, and long-lead (beyond two weeks) forecasts each mentioned three to four times. Other concerns brought up at least once included tornados, tropical convection, aviation hazards, atmospheric rivers, the Arctic environment, and the importance of research to identify the fundamental limits of predictability.

Attendees recognized the importance of maintaining and expanding NASA's data assimilation and modeling capabilities. The importance of advanced data assimilation, including coupled systems (e.g., atmosphere-ocean and atmosphere-land), was brought up in eight slides. High-resolution global models and OSSEs were brought up in six and five slides, respectively. The challenges of big data, adaptive observing capabilities, probabilistic forecasts, regional modeling, and space weather were all mentioned at least once. The importance of NASA's field campaign support was brought up in four slides.

Several slides highlighted the importance of research to operations/application programs to integrate recent findings and discoveries more quickly into NWS operations and private sector partner applications. Also mentioned was the need to have better collaboration between modelers and observationalists.

In summary, while there was a variety of concerns in the attendee slides, a few prominent themes emerged. These included the importance of high spatial and temporal wind, temperature and water vapor profiles, and the importance of advanced modeling, data assimilation, and OSSE capabilities. Appropriately, given the challenges that lie ahead in developing these capabilities, the necessity of interagency collaboration was also highlighted.

Key Physical Processes in Weather



3

THE FIRST BREAKOUT SESSION ON DAY 2 was divided into three groups focusing on the key physical processes in weather research and forecasting: convection and precipitation, PBL and ocean/land surface, and clouds and radiation.

3.1 Convection and Precipitation

Convection and precipitation play a primary role in many high-impact weather events over a broad range of temporal and spatial scales (e.g., severe storms, tropical cyclones, floods, MJO, etc.). At the same time, these processes have proven particularly challenging to accurately simulate and forecast. Specific difficulties in understanding and representing these processes include the challenge that convective clouds often exist at scales that are only partially resolved by the model. Furthermore, it is difficult to observe and represent the multi-scale interactions that are critical to convective organization and evolution. The high impact of these processes, and the challenges in understanding and simulating them, make convection and precipitation high priority research topics for the NASA weather focus area.

While the topic itself is very broad, the convection and precipitation (C/P) breakout group identified four questions of fundamental importance for understanding and simulating convection and precipitation:

- How do convection and large scale circulations interact? A small subset of examples of the phenomena and processes of interest include tropical cyclones and their upper-level outflow, tropical convection and the MJO or monsoon circulations, continental mesoscale convective systems and mesoscale convective complexes, and extratropical cyclones.
- What determines the mesoscale organization, internal structure and dynamics, and life cycle of convective systems?
- What modulates the rate at which convective storms (of all types) intensify?
- What processes and interactions control the type, onset, rate, and accumulation of precipitation?

The C/P group listed specific measurements that are needed to advance progress on these fundamental questions. These included:

- Wind observations of both the environment and within the convection itself (of particular importance are environmental shear and divergence, and horizontal and vertical velocities within convection);
- Moisture and temperature profiles;
- Cloud microphysical information;
- Chemical composition (including CCN, IN, etc.); and
- Precipitation (type, onset, rate, and quantitative accumulation).

Fine-scale observations that could yield information about latent heating, momentum and mass fluxes, entrainment rates, and the energy cycle between convection and the environment, were also considered very important. For the precipitation question, it was noted that land and ocean sources of water vapor and aerosols are needed globally, and there is a need for observations of regions and precipitation types not well covered by current observations (e.g., polar regions, steep terrain, etc.). The utility of lightning data for data assimilation and verification was brought up in the plenary discussion session at the end of the Workshop, and there was general agreement about the potential value of this.

The C/P group recognized the geographical and phenomenological diversity of the systems of interest and also noted that scale interactions and teleconnections can lead to regional and global impacts. The group also recognized the need to observe these phenomena throughout their lifecycles. The global reach of NASA's observing capabilities makes it uniquely well-suited to address these needs and, therefore, NASA has a key role to play in tackling these basic research questions.

The group also discussed how the observation requirements for process studies and model development purposes are different from observation requirements for data assimilation and reanalysis purposes. NASA plays a fundamental role in both these efforts through their space-based observing capabilities, airborne observing capabilities, and field campaign support.

It was recognized that the temporal and spatial scales of interest will vary widely and depend on the specific phenomena being studied. The C/P group thought that recommendations on the specific temporal and spatial observation requirements, while very important, were beyond the scope of the current Workshop. Research to identify these important requirements should be addressed by the wider community under specific projects, leveraging NASA capabilities and resources.

In summary, the group identified four fundamental questions for better understanding and simulating convection and precipitation. While the observations needed to address these problems were listed, it was noted that spatial and temporal resolution/duration requirements would vary widely depending on the phenomena considered, and identification of these important requirements should be provided by the wider research community. The global reach of NASA's observing capabilities makes it uniquely well-suited to address the global scope and wide variety of observations needed to tackle these fundamental questions and advance progress in the understanding and representation of convection and precipitation.

3.2 Planetary Boundary Layer (PBL) and Ocean/Land Surface

The group started with a general discussion on key challenges in weather research related to the PBL and the land and ocean surface. The key issue of the role of NASA's weather program versus NOAA and other national agencies was debated. In particular, the issue of how much the entire numerical weather prediction enterprise should be, and is, driving weather science and research at the national and international level was a topic of active discussion. The group did not come up with any final conclusions on these two key issues, but agreed that these important general aspects should be prominently mentioned in the final Workshop report.

It was also clear that while many science questions could be identified as important, a long list of fairly specific science questions would not be of great use as an outcome of the Workshop. In this context and after much discussion, the group agreed on the following key weather themes in boundary layer and surface interaction that the community needs to better observe, model, understand, and forecast in the future:

- The interaction of moist convection with the boundary layer and the surface;
- Boundary layer clouds: fog and low clouds are key unsolved forecasting problems; and
- Turbulence as it pertains to moist and dry situations; e.g., boundary layer top entrainment, lateral entrainment, and clear air turbulence generated by the interaction of gravity waves with topography.

Two additional topics—which may not be explicitly referred to as weather themes—were raised as particularly relevant in the context of weather research: (a) a special mention was made of Arctic weather problems in the context of the recent strategic and economic interest in the Arctic region due to significant changes in sea ice coverage and thickness and observed climate change; and (b) air quality and atmospheric composition in the boundary layer are key areas of Earth sciences which are hugely affected by weather.

To have a focused discussion and to provide specific recommendations, the group looked for a common denominator to all three key weather themes mentioned above. In particular, it was found that surface heat and momentum fluxes play an essential role in all of the above themes. In this context, it was recognized that observational estimates of these fluxes from space are still quite deficient and that more accurate estimates are necessary.

The fairly straightforward formulas for estimating surface evaporation, sensible heat, and momentum fluxes were discussed in detail and that allowed us to focus on the key variables in these formulas. This helped focus the discussion on each of the key variables that need to be better measured from space: (i) water vapor in the lower boundary layer, (ii) temperature in the lower boundary layer, (iii) wind in the lower boundary layer, (iv) water properties of the top ocean/land surface, and (v) temperature of the top ocean/land surface. The conversation then focused on each one of these variables: how well do we measure them and what new technologies (both hardware and software) would be needed to improve these estimates.

Regarding water vapor in the boundary layer, the shortcomings of using microwave (MW) vertically integrated water vapor (i.e., water vapor path) to estimate the water vapor closer to the surface for use in surface evaporation formulas were clearly highlighted. Current space-borne technologies like infrared (IR) and GPS RO are able to provide some more information on boundary layer water vapor. In particular, fairly feasible improvements in both IR and GPS RO measuring technologies should be able to provide more detailed water vapor information in the boundary layer in the near future (e.g. better horizontal and vertical resolution). Active systems such as lidar and radar may be able to provide more detailed boundary layer water vapor measurements in the long-term future.

In terms of temperature, it was clear from the group discussion that improvements are needed to produce better lower boundary layer temperature measurements from space. Again IR and GPS RO measuring technologies can already provide some information and further improvements in terms of horizontal and vertical resolution are feasible in the near future.

For wind, there was some agreement that scatterometer winds over the ocean are fairly accurate and play an important role in improving forecasts (e.g., hurricane forecasting). Wind observations from space over land and close to the surface are a whole different and difficult problem. Several aspects of potential wind measurements were debated: desired accuracy, range, temporal resolution versus accuracy and horizontal and vertical resolutions. Land surface variables such as skin temperature and soil moisture are also essential to produce more accurate estimates of surface latent and sensible heat fluxes. Issues such as temporal and horizontal resolution and accuracy were highlighted.

Many other general yet important topics were discussed by the group, including: (i) in-situ observations and field experiments; (ii) monthly weather prediction as a key direction that weather prediction centers should follow; (iii) the essential role of data assimilation systems; (iv) utilization of simulators to better design future observational missions; (v) specific long term prediction problems such as drought; (vi) and a variety of weather applications related to the boundary layer such as fire and wind and solar energy forecasting.

In summary, the group focused on three key weather themes. Improved estimates from space of surface heat, water, and momentum fluxes would be essential to improve our forecasts of each of these three weather themes. In order to achieve this goal, better measurements from space of temperature, water vapor, and wind in the lower part of the PBL are necessary. Better measurements imply better horizontal, vertical, and temporal resolutions as well as better accuracy.

3.3 Clouds and Radiation

The breakout discussion began with a round of brainstorming about the measurements needed to improve the capability to predict weather through information on the environmental state of clouds, radiation, and their coupling. This list was then condensed into four broad themes. The discussion suggested that satellite observations can potentially play two roles—improving model physics by providing cloud microphysics over a 3-dimensional volume and also by providing information about temporal evolution of cloud macrophysical characteristics to give a 4-dimensional view. In the context of broader storm scale/environmental factor information, the high temporal and spatial resolution observations can be assimilated to constrain initial conditions in models. Below are three topical areas where discussions focused.

Theme #1: Cloud microphysical properties (ice clouds in particular), connections to aerosols and precipitation

A big challenge in improving our understanding of clouds and precipitation is gaining insights into the processes that govern where precipitation forms and its intensity. Specifically, we need to document the environmental factors that determine the relative contributions of various ice and liquid phase processes (deposition, aggregation, riming, accretion, melting, entrainment, and evaporation) to precipitation development and how these processes relate to convective motions in the atmosphere. These are the processes that are currently very crudely parameterized in most weather models, yet ultimately define the system precipitation and, consequently, societal impacts. Cloud and convection permitting models that do represent these processes more explicitly exhibit extreme sensitivity to the choice of process rates. For example, a small change in the relative rates of aggregation and riming that is well inside bounds suggested by our current level of understanding, can lead to differences of a factor of 4 in precipitation accumulations from mid-latitude cyclones.

Observations are needed that can more directly constrain these rates on various weather scales and quantify their dependence on the environment, including factors that may change in a warmer climate such as increased water vapor convergence. We need measurements that simultaneously provide access to cloud and precipitation microphysics and mass fluxes from which gradients can be used to estimate process rates and associated thermodynamic responses due to latent heat release. The discussions particularly emphasized the need for ice cloud properties, including integral properties such as ice mass distributions.

Theme #2: Spatio-temporal distribution of clouds (diurnal characterization)

There is a need for the horizontal, vertical, and temporal distribution of cloud properties. The current NASA A-train observations have enabled snapshots and composites of the spatial structure of clouds in particular weather system as well as global patterns. There is also information on temporal changes in weather systems through snapshots at the life-cycle of particular storm systems, but there is not a high temporal resolution monitoring of the three dimensional structure of clouds.

MODIS, CloudSat, CALIPSO, and GPM can be used to characterize the spatial structure, but there remains a need to understand diurnal variation of cloud systems. For example, characterizing rapid intensification of storms is a challenge in improving weather system prediction, and will likely be in the foreseeable future. With regard to hurricanes, there is still a need to better understand the forcing mechanisms (environment versus internal dynamics), and vortex-scale observations are hard to come by (hence, the many field programs of late focusing on hurricanes). Current satellites have gotten better at measuring environmental variables (moisture, temperature, wind, and sea surface temperature), and the microwave sensors on LEOs get us some proxy information on vortex structure (precipitation bands, warm core), but not with the precision or timeliness necessary for process studies.

Theme #3: Data assimilation of clouds in weather models (what measurements would make a difference?)

The data assimilation of clouds in weather models remains a large challenge. It is not clear what cloud properties are actually needed to be assimilated into a model. Is it enough to have the presence of a cloud or are the bulk or detailed cloud microphysical properties needed? Progress in cloudy data assimilation has been made with respect to high-resolution models but many global models still use crude parameterizations coupled with total water path. Incorporating realistic cloud processes is important because it will allow data assimilation systems to use the full information content that future satellite sensors provide.

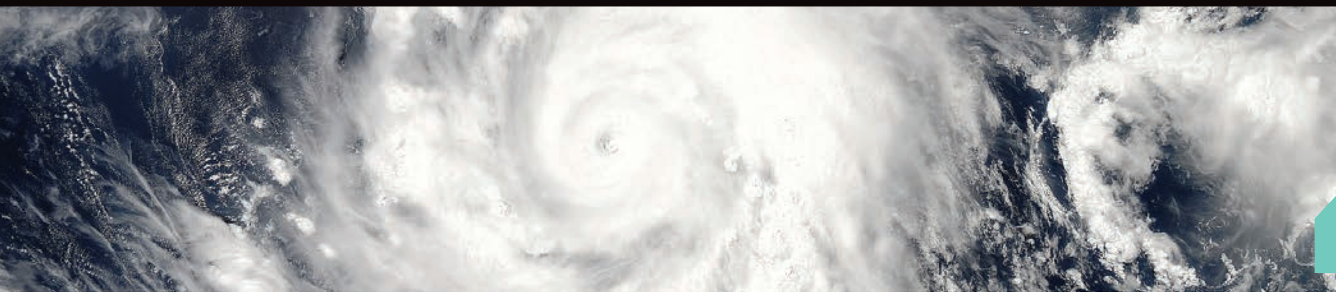
Data assimilation of clouds in weather models requires high resolution satellite observations in both space and time. Satellite observations individually will never be as useful for model validation and data assimilation purposes as in situ cloud observations; however, this deficiency can be rectified through access to large data volumes. This means a need for observations from geosynchronous satellites.

There remain several challenges when it comes to using cloudy satellite observations for data assimilation. First, the quality of the assimilation is dependent on the quality of the model background, which can be really bad for cloud fields. Some of this is due to the fact that many of the parameters in cloud microphysical parameterization schemes have a wide range of potential values, yet are often set to a constant value either for convenience or due to a lack of observations. This again points to the need to provide more information about the cloud particle distribution to support model development.

The group concluded that there was a need for **comprehensive global measurements of cloud microphysical properties to understand the impact in weather models and ultimately constrain models to improve predictability.** Specifically:

- There needs to be an assessment and improved use of existing airborne microphysical data sets; analysis of these measurements may improve our understanding of ice cloud microphysical properties and reveal inadequacies in existing data sets that will guide future sensor development and field project design.
- Better measurements of particle size distribution and bulk ice properties are needed to improve our understanding of clouds and precipitation and to gain insights into the processes that govern where precipitation forms and its intensity.
- While it is not clear what cloud properties are actually needed to be assimilated into a model, it is likely that data assimilation of clouds in weather models will require high resolution satellite observations in both space and time.

Key Weather Science, Technology, and Modeling Challenges



4

THE SECOND BREAKOUT SESSION ON Day 2 was divided into three groups focusing on the science questions [including (weather-to-climate transition) sub-seasonal to seasonal issues], new instruments/technology (including emerging and underutilized existing instruments), and modeling/data assimilation.

4.1 Science Questions in Weather Research and Forecasting

The breakout group discussion on science questions was prefaced by an explicit acknowledgement of the current NASA Weather Focus Area Baseline from NASA Science Mission Directorate Web page (as also mentioned in Section 1). The four guiding principles of the current focus are:

- Weather systems include not only the dynamics of the atmosphere but also interaction with the oceans and land.
- Weather includes local or microphysical processes that range in temporal scales from minutes to two weeks.
- Weather as a societal benefit area is strongly tied to climate, the water cycle, and energy.
- In addition to performing fundamental Earth science research for weather, NASA plays a very important role in the introduction of new technologies for use by operational weather agencies.

The breakout group agreed that these continue to be sound principles and that this Workshop's challenge would be to formulate the most appropriate and forward-thinking science questions to advance them over the next decade.

As a research agency, NASA has particular advantages in pursuing Earth science research to advance observations, scientific understanding and predictive capability in weather. Foremost of these advantages is the global reach of NASA's substantive satellite and sub-orbital system capabilities. NASA is also uniquely equipped to develop and demonstrate new technologies and to focus on the understanding of fundamental weather processes while tolerating much higher risk than the operational weather enterprise.

The science questions which were identified to advance the NASA Weather Focus Area therefore entail a strategic focus that is consistent with NASA goals and builds off the NASA Strategic Plan to improve capability to predict weather and extreme weather events. This evolution of the Weather Focus Area centers on three primary elements to advance weather science and Earth system prediction:

- Multi-scale process studies, data assimilation, and modeling;
- Coupling of the atmosphere, land, and ocean; and
- Improving predictability beyond two weeks.

Cross-cutting process studies need to be at the core of this effort. This includes Earth system coupling, e.g., land/atmosphere coupling; observing system architecture assessment; and bridging the gap between weather and climate models, and between cloud, storm, mesoscale, and synoptic temporal and spatial scales. NASA is also uniquely suited to improve sub-seasonal to seasonal predictive skill for weather and extreme weather events. This research should also directly improve related societal benefit areas through vigorous linkages to applications development and partnerships for the transition of this research to operations and applications.

This discussion identified the fundamental questions that the NASA Weather Focus Area must address and is uniquely suited to answer. In particular, basic research in the following twelve areas was entailed:

1. Bridging the weather-climate gap to enable meaningful forecast skill beyond two weeks, and out to seasonal and annual time scales. This is needed to better predict events such as the current California drought.
2. Better understanding of global circulation such as the relationship between global scale (e.g., Rossby wave) perturbations and regional impacts (e.g., atmospheric rivers) and its impact on both canonical weather and extreme weather events. This is also needed to better predict events such as the California drought as well as the more episodic extreme snow events of 2015.
3. Phenomenological and geographic extreme weather event frequency, intensity, and variability and the historic versus current trajectory thereof.
4. Determining the role and nature of Earth system component (ocean, atmosphere, and land) coupling in weather prediction.
5. Small (cloud) scale processes.
6. Interaction between small scale and large (global) scale processes.
7. Understanding limits of predictability for specific phenomena and scales.
8. Variation of extreme weather events with climate change.
9. Factors controlling extreme weather events and the influence of Earth system coupling on them.
10. Determining and overcoming the barriers to improving predictive skill.
11. Understanding uncertainty across time and space scales and its effect on predictability.
12. Moving from deterministic to probabilistic forecasting.

Specific actions were identified to address these questions. The first would be to develop the next generation observing system measurement and research and analysis strategy. NASA must develop new observations to enhance the understanding of Earth system processes that control weather and extreme weather events. This is needed both to improve weather prediction models and initial conditions and to bridge weather and climate scales. Integrating existing and new observations is also needed to improve understanding and representation of coupled processes in weather models. In doing this, NASA must also consider operational weather agency science gaps and observation needs to assist in establishing NASA science priorities.

This breakout group lacked the time, resources, and people to completely flesh out these priorities; however, we were able to end the session with a discussion of salient examples of extreme weather events. To advance weather science and Earth system prediction related to extreme weather, it is important to recognize that extreme weather phenomena (e.g., flooding, winter weather, hurricane intensity) are influenced by fundamental factors. There are also significant barriers to predictive skill which control the frequency, onset, location, and intensity of extreme weather events.

Extreme weather phenomena also vary with climate variability and change. These influences are different for the panoply of extreme weather phenomena and events which range across the spatial and temporal landscape. However, guidance on the operative scales and science research gaps exists in the peer-reviewed literature, and in federal plans such as FCM-P36-2007 from OFCM (Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead, February 2007). Resources such as this can provide particular insight for research needed to improve the predictability of extreme weather events and to identify both the unique and cross-cutting spatial and temporal scales and science gaps that must be addressed.

The final discussion explored the differences as well as the cross connections of scales for several different examples. Hurricanes, their extra-tropical transition, and the accompanying storm surge entail processes span all spatial scales from the convective cloud process scale to thousands of kilometers. We similarly discussed severe weather, which includes hail, tornados, and other damaging winds (convective downdrafts, straight-line, etc.) as well as dangerous lightning. Winter storms also operate at all of these scales and present additional challenges with respect to forecasting snow accumulation and location. Wind shear, stability, thermodynamics, longer range predictions, as well as scale interaction and their effects on predictability (the NWS Warn-on-Forecast concept) also present major research challenges and opportunities.

Finally, as we move beyond the synoptic scales to embrace global regimes and time scales beyond two weeks or more for predictability, extreme events such as drought and heat waves provide fertile areas of needed research. Even here, however, the longer and larger scales normally associated with climate science must be considered within the context of weather, where a better understanding of atmospheric rivers, their perturbation and displacement, is key. New ways of thinking about these phenomena are needed. The teleconnections which exist between them and also a better understanding of unique hydrological, meteorological, and agricultural drought parameters are all areas of needed research.

4.2 New Instruments/ Technology

This breakout group included about 20 participants whose expertise covered the spectrum from new technology development to numerical weather prediction. Since this session was in the second group of breakouts, participants were able to frame the discussions in the context of the ideas brought forward in the Convection & Precipitation (Section 3.1), PBL/Ocean & Land Surface (Section 3.2), and Clouds & Radiation (Section 3.3) sessions that occurred earlier. The discussions were conducted as an open forum, with participants raising issues that sparked questions and new threads of conversation. The presentation of NASA investments in Earth science technology (managed by ESTO) was available for reference during the discussion. NOAA does not develop new instruments, so this is clearly a NASA-unique capability and responsibility.

3D winds were mentioned many times during the first day's plenary and participant talks and resulted in the first set of discussions. NOAA participants indicated a burning need for 3D wind data for NWP. Errors in tropical winds can often corrupt the forecast. Assimilation of wind data shows tremendous impacts on hurricane forecasts—more so than any other observations. Two technologies currently exist for the remote sensing of winds—lidar in clear air and Doppler radar in the presence of clouds and precipitation. Lidar depends on returns from aerosols and molecules, and generally works anywhere in optically thin regions. Radar depends on returns from hydrometeors and can make satisfactory measurements in clouds and precipitation if the right frequencies are selected. A third approach is to use hyperspectral infrared measurements (in an AMV wind triplet) to measure wind profiles.

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. The group did not have a good feel for the measurement requirements (temporal and spatial resolutions), which drive the system requirements for a wind-observing system. There is a perception that wind measurements would be prohibitively expensive—but that notion depends on the system configuration and comprehensiveness of the measurement. The question also arose as to what is meant by 3D winds? Is the 3D (u, v, w) vector necessary? Are horizontal wind fields (u, v) sufficient? Is vertical motion inside convective systems sufficient? What temporal sampling is required? The answer depends on the science question. All of these drive the system complexity, and ultimately cost, so a clear understanding of a measurement's impact on the particular investigation is needed before the feasibility can be assessed.

A decade ago, Congress mandated that NOAA and NASA pursue data buys of wind data from private sources. Researchers at NASA were tasked with defining the minimum wind measurement requirements to ensure a positive impact on NWP. With the observing system having substantially evolved since that time, it is probably necessary to do a new assessment (building on the document from the previous assessment).

This need for a new assessment led to a discussion of OSSEs, which are very mature for NWP and less mature for measuring other kinds of observing system impacts on science investigations. NOAA and NASA both have OSSE capabilities which are currently underutilized for assessing measurement impacts. The group was in general agreement that doing these kinds of experiments to determine the impacts of a proposed measurement system is very important in trade studies leading up to mission definition.

However, the NASA process for soliciting competed missions places such analysis after proposal selection, where it has the most limited impact. Ideally, OSSEs should be performed during proposal formulation, where mission systems trade studies can be done against impact and cost. A validated OSSE capability, however, requires substantial infrastructure and expertise, which is not generally available to the community. Since such capabilities currently exist within NASA and NOAA, it was suggested that **a unified NASA-NOAA OSSE infrastructure be implemented at marginal additional cost and be made available for system impact assessments prior to proposal formulation**. This notion was particularly attractive to ESTO, which needs guidance in formulating the most cost-effective investments for future technology development.

There is also a need to develop instrument simulators that can be utilized within OSSEs as new measurements are proposed. ESTO has invested in these in the past, and capabilities do exist at NASA centers. It is likely that continued investment would be beneficial as OSSE capabilities mature.

Having a mature OSSE capability would be beneficial for sorting out the impact of wind measurement technologies. Radar and lidar measure line of sight winds, so constructing 3D wind profiles require multiple look-angle measurements, which lead to observing systems with complicated system configurations. There is a notion, however, that line of sight may be "good enough" for near term goals. Testing the impact of space-borne and airborne radar and lidar measurement systems would be very useful in understanding the temporal and spatial resolution requirements and setting the Weather Focus Area priorities for winds in the near term.

Temperature and water vapor measurements are also important to the Weather Focus area. Instrument technologies for making these measurements (e.g., radiometer, GPS, lidar, radar) are thought to be well in hand. The drivers of future space-based measurements seem to be temporal revisit and resolution, which lead to constellation systems and/or geosynchronous platforms and drive aperture requirements and power. ESTO is investing in geo-based sounders and small-sat and cubesat versions of these technologies. The group did not have a clear understanding of requirements for these kinds of measurements as they might relate to convective systems. These measurements can be made inside of convective systems from space, but temporal sampling requirements will be the challenge if complete storm evolution sampling is desired.

Clouds and precipitation measurements were also discussed in the context of the identification of the spatio-temporal evolution of clouds and cloud hydrometeor properties as priorities. The existing investments in sounder and radar technologies appear to be sufficient for making the desired measures, but again the challenge is in the temporal sampling desired. Current measurements are aircraft or low-Earth orbit–based and do not cover either the spatial sampling or temporal sampling that seems to be desired. The group expected that the continued use of aircraft field campaigns would be required, particularly for high resolution measurements within and around clouds. But these are limited in temporal extent, are not comprehensive in spatial sampling, and are episodic at best. Space-based radar for hydrometeor characterization and precipitation, sounders for precipitation, temperature, and water vapor, and lidar for water vapor and aerosol are all in the current investment portfolio, and could be matured to flight-ready systems within relatively short time periods by targeted investment, if a specific measurement need was deemed to be high priority.

It was noted that in many instances, what might be needed is collocated measures of several physical parameters over the evolution cycle of the phenomenon, involving multiple instruments. This points back to the need to be able to study the effectiveness of system-level measurement concepts by varying the number and types of observations across spatial and temporal scales. It was thought that a mature OSSE capability would be very effective for these kinds of studies.

The group also spent a relatively short period of time towards the end of the session talking about future needs. The consensus was that ESTO is currently making the right investments to meet the present observational needs. However, in looking forward to the next decade, it is important to also continue investing in new high-risk measurement concepts to seed the technology portfolio for the following ten years. ESTO agrees that this is important, and seeks guidance from the Weather Focus Area on the measurement challenges that are the highest priorities. Some longer-term challenges for radar and lidar are in apertures and antennas, which are the current limiting factors on measurement spatial resolution. Temporal revisit requirements with high spatial resolution could potentially be satisfied by geosynchronous platforms, but this approach depends on the availability of mature (probably deployable) microwave and radar apertures spanning 10 meters or more.

Ocean vector winds were also briefly touched upon. The current and emerging scatterometer technologies were thought to be well in hand, and no other measurement gap was identified.

There was no substantive discussion of land surface measurements or information technology during this session. The extended discussion of wind measurements and OSSEs compressed the time available for the other topics in the session, and information technology was set aside in favor of the measurement discussions. It was noted that retrieval algorithms continue to need investments and in particular, the ability to use collocated radar, lidar, and radiometer observations is expected to be an enabling future capability.

In summary, the group reviewed the current NASA measurement capabilities and ESTO technology investments related to weather research. Much of the discussion revolved around the measurement of winds, both in clear air and within convective systems, and OSSE capabilities for assessing the impact of a particular measurement on forecast systems and science investigations. Technologies for measurement of atmospheric temperature, water vapor, precipitation, and cloud hydrometeors were thought to be well in hand, but continued technology investments are encouraged to meet future observational needs.

Furthermore, the challenges in weather science are expected to be at the systems level—combinations of measurements to cover the key temporal scales of rapidly evolving systems. These likely involve a combination of satellite, ground, and aircraft observations. A mature OSSE capability is needed to assess the impact of various systems concepts. The key finding and recommendations from the group are:

Findings

- Mature or emerging technologies exist to make the measurements thought to be important to the Weather Focus Area.
- A key problem for weather research is understanding the requirements for temporal and spatial sampling, which drive system level measurement requirements, and, ultimately, cost.
- OSSEs could play an important role in assessing the impact of an individual measurement, or a system of measurements, on the ability to answer a science question and improve NWP forecast skill.
- The major technology gaps for the future are thought to be large apertures for high resolution geosynchronous radar and sounder spatial sampling and constellations for high temporal sampling.

Recommendations

- The Weather Focus Area should take ownership of an Earth Science OSSE capability for assessing the impact of measurements and measurement systems on the ability to answer science questions. The key outcome from such experiments is to determine when a concept measurement system is "good enough" to make progress. The recommendation is for incremental investment to make current capabilities operational in the process of system trade studies. It is not a recommendation to take ownership of the modeling and data assimilation infrastructure.
- Serious consideration should be given to joining NASA and NOAA OSSE capabilities into a unified infrastructure.
- The Weather Focus Area should prioritize its measurement requirements, so that appropriate investment can be made in emerging technologies to advance them to flight ready status. Given that current technology investments already exist for all of the measurements thought to be important to weather research, it is simply a matter of investment in technology maturation to bring a measurement system to fruition.

4.3 Modeling and Data Assimilation

To complement its suite of Earth-observing satellites, NASA supports a forefront effort in modeling and data assimilation, which is a major component of the Weather Focus Area. The major modeling and assimilation activities are centered on the global GEOS-5 and the regional WRF systems, supported by the high-performance computing resources offered at GSFC and ARC.

Discussions focused on the need for NASA to support a sustained, high-resolution modeling capability directed first at using all observations to their fullest extent in weather prediction and second at planning for new global observations. The importance of a sustained investment in high-performance computing techniques was emphasized, as was the need for enhanced data-distribution techniques as we move into a period when multi-petaflop computing capabilities generate multi-petabyte (to exabyte) datasets.

It was recognized that today's forefront models, which include increasingly complex processes and resolve ever-higher spatio-temporal resolutions, are the prototypes for the operational systems on the five-year time horizon. Forefront global models are running on grids with resolutions of several kilometers, which fall short of the cloud-resolving scale. To support development of new observing systems, as well as enhanced representations of physical processes suitable for use on the few-kilometer scales, a priority area for NASA research is the investment in cloud-resolving systems down to the sub-kilometer scale. Advances in atmospheric modeling will focus on representations of water and its phase transitions, as well as on clouds and aerosols and their couplings. Representations of land, ocean, and ice are an important factor, as exchanges of energy, momentum, and moisture are major factors in atmospheric predictability, yet they are not directly observable. Coupled land models will need enhanced representations of hydrology, including snow and ice components. Developments in ocean modeling for weather applications will require an enhanced representation of the physical ocean, to accommodate surface exchange processes, as well as broader use of wave modeling to improve representations of coastal processes and also to help enhance the use of surface-wind observations in NWP.

Realistic models form the basis for OSSEs. NASA's use of forefront computing systems to generate high-resolution "nature runs" is a major contribution to planning new observations. The ability to simulate the current observing system from the model simulations is a pre-requisite for syntheses of potential new observing types. Future space missions devoted to observations of clouds and precipitation motivate the need for global simulations on sub-kilometer scales, which then form a basis for development of observation strategies and the techniques to include such observations in global data assimilation systems. The application of OSSEs to the impacts of new observation types on "weather forecasts" is now a well-established exercise, with widely accepted metrics that evaluate success (e.g., the impact of a new observation type on the five-day forecast skill). A bigger challenge that will underpin development of future NASA "weather" missions is the quantitative valuation of observation impacts on localized weather conditions, especially on extreme events such as hurricanes, storm systems, and tornadoes. Recurrent discussion points were the need to develop and use OSSEs that test the impacts of cloud and precipitation observations and of different types of wind observations, all of which are potential candidates for new satellite instruments in the next years to decades.

Developments of assimilation systems build on advances in modeling. There was a general feeling that NASA should advance its data assimilation capabilities in line with developments in other centers. This includes a move towards ensemble-based systems in order to represent flow-dependent error covariances, with consequent experimentation needed to optimize the nature and size of the ensembles. Other challenging technical advances include the need to advance all-sky radiance assimilation, with consequent needs to improve the representation of microphysical processes in the forward models and include these impacts on observation operators. As model resolution increases, they can resolve scales that are comparable to satellite footprints. This advantage can be exploited in data assimilation only if the model physics has a high degree of integrity. The need to introduce non-linear data assimilation techniques is an important advance in this context. Further, the need to improve coupling of the atmospheric state in unison with the underlying land, ice, or ocean surface is an important requirement for future analysis systems, as this improves the representation of physical balances (energy, moisture, etc.) in the system.

In summary, a sustained modeling and assimilation framework is central to the ongoing development and success of NASA's Weather Focus Area. Development and application of complex, coupled model systems will enhance the use of NASA's observations in weather analysis and forecasting systems, enabling the impacts of novel information to be assessed. This will promote the transition of suitable research-type observations into operational systems at NOAA/NWS. Forefront model simulations are essential to the pre-selection planning of potential new missions, through the use of OSSEs and other techniques. These complex modeling and analysis systems will span the atmosphere, land, oceans, and cryosphere. They will also include a range of scales, from global mesoscale to cloud-resolving scales.

Findings and Recommendations

5

THE GOAL OF THE WORKSHOP WAS TO identify the most challenging scientific research and development topics that can be uniquely addressed by the Weather Focus Area. These topics would draw on NASA's satellite, airborne, and surface observations, computational modeling and data assimilation systems, instrument (airborne and satellite) platforms, and high-end computing facilities. The topics are addressed from different perspectives in Sections 2–4. As a synthesis of these discussions, the findings and recommendations are summarized here. **They represent a snapshot of the community's views on selected topics, rather than a comprehensive review of all weather-related topics.**

5.1 Science Questions

Using NASA's capabilities in observations, modeling, and data assimilation 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, the questions include:

- What are the scientific advances and observations needed (e.g., for DA and initialization of the Earth System) to expand the useful range of NWP from 0–2 weeks to 0–4 weeks? For instance, the scientific advances may cover enhanced understanding and simulation of atmosphere-ocean coupling, atmosphere-land coupling, troposphere-stratosphere coupling, and nonlinear interactions in the atmosphere.
- 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 instance, the scientific advances may include quantifying limits of predictability and its variation with climate change, or the development of novel convection parameterizations.

For convection and precipitation, the questions include:

- 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 (of all types) 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 PBL and land/ocean surface processes, the questions include:

- How does moist convection interact with the PBL and the surface?
- What are the fundamental mechanisms controlling boundary layer clouds (including fog)?
- How can we unify the parameterization of moist and dry turbulence and convection (including PBL-top entrainment and lateral entrainment) and clear air turbulence?

For clouds and radiation, the questions include:

- 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 (e.g., winter storms, hurricanes, and tropical convection)?

5.2 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 observation types. 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 observation types in the context of the existing observing system and, hence, to estimate the value of potential new missions.

a) OSSEs

The concept of OSSEs is mature for NWP, in that widely accepted metrics exist to estimate the impacts of new data types on the forecast skill. The OSSE concept is not as well developed for other types of impact study, where the metrics of success are not yet well defined or where the end goal is a beneficial impact on a science investigation. NASA and NOAA have OSSE capabilities which are currently underutilized for assessing measurement impacts that are very important in trade studies leading up to mission definition. Ideally, OSSEs could quantitatively:

- determine the potential impact of proposed space-based, suborbital, and in situ observing systems on weather analyses and forecasts, including potential impacts on the advanced prediction of extreme weather events;
- evaluate and compare the merits of a range of observing system design options; and

- assess the relative capabilities and costs of various observing systems and combinations of observing systems.

A key aspect is that for OSSEs to be useful, the "nature runs" should be as realistic as possible. In this context, simulations of the real atmosphere (often referred to as "nature runs") should be conducted with models that have the optimal physics and resolution. These "virtual atmospheric simulations" would depict the specific weather process that is being studied in a realistic manner. For example, to simulate deep convection and storms in a global context, a global cloud resolving model should be used.

OSSEs should be conducted prior to the acquisition of major government-owned or government-leased operational observing systems, including polar-orbiting and geostationary satellite systems, and prior to the purchase of any major new commercially provided data.

A comprehensive OSSE system for weather is a large-scale project that would be much more efficient in the context of a multi-agency collaboration. NASA has already provided leadership and moved the field forward by providing high-resolution nature runs and numerous instrument simulators.

However, the NASA process for soliciting competed missions places such analysis after proposal selection, where it can at best inform the implementation, rather than the overall mission design.

Recommendation: 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 done against impact and cost for satellite missions 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.

b) Wind Structure

Global wind measurement is one of the next frontiers for satellite remote sensing, particularly for weather research and forecasting. Based on our fundamental understanding of adjustment processes in the atmosphere, the 3D wind vector (u, v, and w components) is most important for small-scale weather (e.g., convection). In the tropical atmosphere, the absence of geostrophic balance means that wind cannot be inferred from measurements of the thermal structure; therefore, direct measurement of the evolution of horizontal wind vector is important. Even in middle and high latitudes, direct measurement of the horizontal wind field is valuable to include the ageostrophic components, which is critical for the evolution of weather systems.

Technologies currently exist for the remote sensing of winds. Lidar can measure wind in clear air based on returns from aerosols and generally works anywhere in optically thin regions. Radar can make satisfactory wind measurements in the presence of clouds and precipitation based on returns from hydrometeors. AMV wind can also be estimated from multi-platform (GEO and LEO satellites) and multi-angle imagers as well as hyperspectral infrared vertical profilers. The expense of wind measurements will vary substantially, depending on the technique used (e.g., active or passive), the comprehensiveness of the measurement (e.g., vertical profiles or discrete levels), and the required accuracy of the measurement. The value of any observation thus depends on the impact on the science questions to be addressed.

Recommendation: Global measurements of the spatio-temporal 4D evolution of large-scale horizontal wind vectors are urgently needed. It is important to avoid all-or-nothing strategies for the 3D wind vector measurements, as important progress is possible with less than comprehensive observing strategies. Some additional trade studies may still be needed to design the most cost-effective strategy for wind measurements (based on lidar, radar, and AMV) from satellites and airborne flights.

c) Temperature and Humidity Measurements

Steady progress has been made in instrument technologies for making temperature and humidity profile measurements. The drivers of future measurements seem to be temporal revisit and spatial resolution, which could lead to constellations and/or geosynchronous platforms and drive aperture requirements and power. ESTO is investing in GEO-based sounders and small-sat and cubesat versions of these technologies.

Recommendation: Continuous investment in temperature and humidity measurements is needed, particularly focusing on higher spatial and temporal resolution and synergistic (e.g., A-train type) measurements involving multiple instruments (e.g., infrared, microwave, GPS RO, radar, lidar), different platforms (GEO, LEO, airborne), and different types of satellites (including small-sat and cubesat). Better measurements from space of the temperature, water vapor, and wind in the atmospheric boundary layer are needed to estimate more accurately ocean/land surface turbulent fluxes closely linked to boundary layer and convection processes.

d) Cloud and Precipitation Measurements

The existing investments in sounder and radar technologies for clouds and precipitation measurements appear to be sufficient for making the desired measurements, but, again, the challenge is in the temporal sampling desired. In addition, there needs to be an assessment and improved use of existing airborne microphysical data sets; analysis of these measurements may improve our understanding of ice cloud microphysical properties and reveal inadequacies in existing data sets that will guide future sensor development and field project design.

Space-based radar for hydrometeor characterization and precipitation, sounders for precipitation, temperature, and water vapor, and lidar for water vapor and aerosol are all in the current investment portfolio. They could be matured to flight-ready systems within relatively short time periods by targeted investment, if a specific measurement need is deemed to be high priority. In particular, better measurements of particle size distribution and bulk ice properties are needed to improve our understanding of clouds and precipitation and to gain insights into the processes that govern where precipitation forms and its intensity.

Recommendation: Continuous investment in cloud and precipitation measurements is needed, particularly focusing on higher spatial and temporal resolution and synergistic (e.g., A-train type) measurements involving multiple instruments (e.g., radar, radiometer, and lidar observations), different platforms (GEO, LEO, airborne), and different types of satellites (including small-sat and cubesat). Particularly relevant to these measurements is the estimate of the vertical velocity.

5.3 Modeling, Data Assimilation, and Computing

Modeling, data assimilation, and high-end computing are an integral part of the NASA Weather Focus Area. For instance, NASA's use of forefront computing systems to generate high-resolution "nature runs" is a major contribution to national efforts in OSSE experiments at other agencies for planning new observations. A sustained modeling and assimilation framework would also promote the transition of suitable research-type observations into operational systems at NOAA/NWS.

a) Modeling

The ability to maintain a forefront modeling capability is a key component of the NASA Weather Focus Area. Today's forefront models, which include increasingly complex processes and resolve ever-higher spatial resolutions, are the prototypes for the operational systems on the five-year time horizon. Realistic models also form the basis for OSSEs. The ability to simulate the current observing system from the model simulations is a pre-requisite for syntheses of potential new observing types.

Modeling activities are carried out at all NWP centers and numerous research centers worldwide. Therefore NASA's priorities in modeling should focus on aspects that are directly linked to NASA's unique observing capabilities, in order to strengthen the links between missions and the Weather Focus Area.

Recommendation: 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, 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) also need to be pursued in parallel.

b) Data Assimilation

Data Assimilation is the bridge between measurements and modeling for weather forecasting. NASA's ability to maintain competitive data assimilation systems is crucial for examinations of the impacts of NASA observations in the context of the global "operational" observing system. For instance, it is not clear exactly what cloud properties can provide the best constraints on models and forecasts, and NASA's research and development activities in data assimilation should include activities in this area. It is likely that the assimilation of clouds in weather models will benefit from the availability of high-resolution satellite observations in both space and time.

Two broad types of advance are needed in the area of data assimilation: the development of accurate operators for new (or previously unviable) types of measurements and the development of the assimilation methodology to provide more comprehensive constraints for the atmosphere coupled with the underlying land, ice, and ocean surface. These developments will involve close collaborations with instrument teams, the use of forefront models, and extensions of the assimilation techniques.

Recommendation: NASA should collaborate closely with operational and research centers and support research on cutting-edge assimilation issues such as: hybrid ensemble-based 4D-Var, all-sky radiance assimilation, assimilation of properties related to clouds and radiation [we don't even know what variables are the correct ones to assimilate for cloud data assimilation], land surface emissivity, coupled data assimilation of the atmosphere-ocean-land-ice system, and data assimilation evaluation metrics.

c) High-Performance Computing (HPC)

In the past many years, NASA has grown the HPC capacity closely following the Moore's law, and NASA-funded projects have enjoyed HPC resources not available to some other agencies. Significant large-scale modeling and data assimilation exercises took place to produce critical data sets like MERRA, AMIP/CMIP, and high-resolution nature runs. NASA has made these critical data sets available to the research community.

With very high-resolution models (e.g., cloud resolving or large-eddy simulation models)—in particular global cloud resolving models—we have moved into an era with petabyte to exabyte datasets from observations and modeling. Data access and discovery also become a significant challenge. In the past couple of years, NASA has invested in large scale data management and data analytic capabilities at the HPC centers. NASA's experience in this area should position it to be a leader.

On the other hand, the growth in the HPC capacity at NASA has slowed in recent years due to the facility limitations (e.g. floor space, power, and cooling). More and more HPC procurement budget has also been diverted to upgrade the computing centers. In order to support ambitious high-resolution modeling activities in the future, NASA needs to not only grow the computing capability but also upgrade the storage, networking and computing center facility.

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

5.4 Other Recommendations

Additional recommendations were also made without extensive discussions:

- MERRA has been widely used by the community, and continuing NASA efforts, such as MERRA-2, are encouraged.

- The Weather Data Record (WDR) using high-resolution global models and with data assimilation of all available satellite data should be developed for major extreme events. This is in contrast to the global reanalysis (usually at coarser resolution and for much longer periods) and to the Climate Data Record.
- Better coordination between instrument developers and model/DA groups needs to be developed.
- In Weather Focus Area, R2O should be among the first considerations in mission development, not the last.

These science questions and recommendations require NASA to work closely with other agencies, academia, the private sector, and international partners, including the leverage of existing partnerships such as the National Earth System Prediction Capability (ESPC) and Joint Center for Satellite Data Assimilation (JCSDA) as well as joint satellite missions with 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 United States 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, data assimilation, and computing efforts are also covered by NOAA, NSF, DOD, and the private sector, NASA's unique role is to focus on modeling and data assimilation 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 data assimilation 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, do 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 data assimilation systems to address these science questions.

Acknowledgements. Tsengdar J. Lee is thanked for initiating and supporting this report. All participants in Appendix B are thanked for their contributions to Workshop presentations and discussions. Robert Atlas, Ken Carey, James D. Doyle, Gary Jedlovec, Jim Kinter, Christian Kummerow, Kevin Maschhoff, Dave McCarren, Amin R. Nehrir, David B. Parsons, Marshall Shepherd, Gail Skofronick-Jackson, Duane E. Waliser, and Elizabeth C. Weatherhead are thanked for their comments and suggestions on the draft report.

Appendix A. Workshop Program

When: 7–8 April 2015 (for all participants) plus half-day on 9 April 2015 (for committee members)

Where: Hyatt Regency Crystal City (near DCA-Reagan National Airport), 2799 Jefferson Davis Highway, Arlington, VA 22202 (Tel: 703-418-1234)

Organizing Committee: Xubin Zeng (Chair; U. Arizona), Carolyn Reynolds (Co-Chair; NRL), Steve Ackerman (U. Wisconsin), Steven Pawson (NASA/GSFC), Joao Teixeira (NASA/JPL)

Advising Committee: Tsengdar J. Lee (Chair; NASA HQ), Robert D. Ferraro (NASA/JPL), John J. Murray (NASA/LaRC)

Web site: *https://www.signup4.net/public/ap.aspx?EID=WORK113E&OID=50*

Day 1

(7 April 2014, Tuesday) (Tidewater 2 Room, 2nd floor)

Session 1 (Chair: Xubin Zeng, University of Arizona)

8:30–8:40 a.m.	**Welcome:** 10 min (Tsengdar Lee, NASA Headquarters; Xubin Zeng, U. Arizona)
8:40–9:10 a.m.	**Current portfolio of the NASA Weather Focus Area:** 30 min Jack Kaye (NASA Headquarters)
9:10–9:40 a.m.	**U.S. weather research:** 30 min Bill Lapenta (NOAA/NCEP)
9:40–9:50 a.m.	**Interagency perspective:** 10 min David McCarren (OFCM)
9:50–10:10 a.m.	**Review of previous weather-related NRC Reports:** 20 min Amanda Staudt (National Academies BASC)
10:10–10:30 a.m.	Break

Session 2 (Chair: Steve Ackerman, University of Wisconsin)

10:30–11:10 a.m.	**Modeling:** 40 min (20 min each) Joao Teixeira (NASA/JPL) and Bill Putman (NASA/GSFC)
11:10–11:40 a.m.	**Data assimilation:** 30 min Ron Gelaro (NASA/GSFC)
11:40 a.m.–12:10 p.m.	**Satellite observations:** 30 min Steve English (ECMWF)
12:10–1:30 p.m.	Lunch

Session 3 (Chair: Steven Pawson, GSFC/GMAO)

1:30–2:10 p.m.	**Field campaigns:** 40 min (20 min each) Gerald Heymsfield (NASA/GSFC) and Vanda Grubisic (NCAR/EOL)
2:10–2:40 p.m.	**Technology:** 30 min Parminder Ghuman (NASA/ESTO)
2:40–2:50 p.m.	**NASA high-end computing capabilities:** 10 min Dan Duffy (NASA/NCCS)
2:50–3:10 p.m.	Break

Session 4 (Chair: Carolyn Reynolds, Naval Research Laboratory)

3:10–5:10 p.m.	**1 slide/2 min from each participant:** 120 min (if you need to leave early, you will be able to talk first)

Day 2

(8 April 2014, Wednesday)

Session 5 (Chair: Robert D. Ferraro, NASA/JPL)

8:30–8:35 a.m. **Charge of the breakout discussion (three groups):** 5 min

8:40–10:20 a.m. **Breakout discussion:** 100 min

A. Convection and precipitation (Tidewater 2 Room; 2nd floor)

Chair: Carolyn Reynolds, Naval Research Laboratory

Rapporteur: Russ Schumacher, Colorado State University

B. PBL/ocean surface/land surface (Roosevelt Room, 3rd floor)

Chair: Joao Teixeira, NASA/JPL

Rapporteur: Shuyi S. Chen, University of Miami

C. Clouds and radiation (Lincoln Room, 3rd floor)

Chair: Steve Ackerman, University of Wisconsin

Rapporteur: Julie Haggerty, NCAR

Emphasis more on **science questions** rather than just operations;

Pay attention to integration and roadmaps;

Include other topics (e.g., upper atmosphere) in the discussions if possible;

Group members to be decided at meeting (1, 2, 3; 1, 2, 3;… so that each group has a good mix of people with different backgrounds).

10:20–10:40 a.m. Break

Session 6 (Chair: Joao Teixeira, NASA/JPL)

10:40–11:10 a.m. **10-min report from each group:** 30 min

11:15 a.m.–12:15 p.m. **Breakout discussion:** 60 min

A. **Science questions [including (weather-to-climate transition) sub-seasonal to seasonal issues]** (Tidewater 2 Room, 2nd floor)

Chair: John J. Murray, NASA/LaRC

Rapporteur: Dave Helms, NOAA/NESDIS

B. **New instruments/technology (including emerging and underutilized existing instruments)** (Roosevelt Room, 3rd floor)

Chair: Robert D. Ferraro, NASA/JPL

Rapporteur: Parminder Ghuman, NASA/GSFC

C. **Modeling/data assimilation** (Lincoln Room, 3rd floor)

Chair: Steven Pawson, NASA/GSFC

Rapporteur: Elizabeth Weatherhead, Univ. of Colorado

Group members will be reassigned with a good mix of people for each group.

12:15–1:15 p.m. Lunch

Session 7 (Chair: John J. Murray, NASA/LARC)

1:15–2:15 p.m. **Breakout discussion** (cont'd): 60 min

A. **Science questions**

B. **New instruments/technology**

C. **Modeling/data assimilation**

2:15–2:30 p.m. Break

2:30–3:00 p.m. **10-min report from each group:** 30 min

3:00–3:30 p.m. **Plenary discussion:** 30 min, integration and roadmaps need to be addressed

Conference ends by 3:30 p.m.

3:30–5:00 p.m. Organizing Committee meeting (Roosevelt Room, 3rd floor)

Day 3

(9 April 2014, Thursday) Morning

8:30–11:30 a.m. Organizing Committee meeting and writing (Arlington Room, 3rd floor)

Appendix B. Participant List

Last Name	First	Affiliation
Ackerman	Steve	Univ. of Wisconsin
Ardanuy	Phil	Raytheon
Atlas	Robert	NOAA/AOML
Bedka	Chris	NASA/LaRC
Birk	Ron	Northrop Grumman
Blackwell	Bill	MIT Lincoln Laboratory
Carey	Kenneth	Earth Resources Technology (ERT)
Chen	Shuyi	U. Miami
Considine	David	NASA HQ
Doyle	James	NRL
Duffy	Dan	NASA/GSFC
Ek	Mike	NOAA/NCEP
English	Steve	ECMWF
Ferek	Ron	Navy/ONR
Ferrare	Rich	NASA/LaRC
Ferraro	Robert	NASA/JPL
Gaier	Todd	NASA/JPL
Gelaro	Ron	NASA/GSFC
Ghuman	Parminder	NASA ESTO/IIP
Gleason	James	NASA/GSFC
Gray	Ellen	NASA/GSFC
Goodman	Steve	NOAA/GOES-R
Grubisic	Vanda	NCAR
Haddad	Ziad	NASA/JPL
Haggerty	Julie	NCAR
Halthore	Rangasayi	FAA
Harr	Patrick	NSF/AGS
Helms	David	NOAA/NESDIS
Heymsfield	Gerry	NASA/GSFC
Higgins	Paul	AMS
Jedlovec	Gary	NASA/MSFC
Ji	Ming	NOAA/NWS
Kakar	Ramesh	NASA HQ
Kalnay	Eugenia	U. Maryland
Kaye	Jack	NASA HQ
Kinter	James	George Mason U

Last Name	First	Affiliation
Kummerow	Chris	Colo St. Univ
Lambrigtsen	Bjorn	NASA/JPL
Lapenta	Bill	NOAA/NCEP
Lee	Tsengdar	NASA HQ
Lu	Chungu	NSF/AGS
Maring	Hal	NASA HQ
Maschhoff	Kevin	BAE Systems
McCarren	David	OFCM
Molthan	Andrew	NASA/MSFC
Murray	John	NASA/LaRC
Nag	Sreeja	MIT
Nehrir	Amin	NASA/LaRC
Novak	David	NOAA/NCEP
Parsons	David	U. Oklahoma
Pawson	Steve	NASA/GSFC
Phillips	Benjamin	NASA HQ
Putman	Bill	NASA/GSFC
Reynolds	Carolyn	NRL
Ritchie	Liz	U. Arizona
Schumacher	Russ	Colo St. U.
Shepherd	Marshall	U. Georgia
Skofronick-Jackson	Gail	NASA/GSFC
Staudt	Amanda	NAS/BASC
Tanelli	Simone	NASA/JPL
Teixeira	Joao	NASA/JPL
Tripoli	Greg	U. Wisc.
Turk	Francis (Joe)	NASA/JPL
Waliser	Duane	NASA/JPL
Wamsley	Paula	Ball Aerospace
Weatherhead	Elizabeth	U. Colo.
Wu	Dong	NASA/GSFC
Yoe	Jim	JCSDA
Yoseph	Elizabeth	Booz Allen Hamilton
Zeng	Xubin	U Arizona
Zhang	Fuqing	Penn St. U.

Appendix C. Acronym List

3D	3-dimensional (in horizontal and vertical directions)
4D-Var	4-dimensional variational (data assimilation)
AGS	NSF Division of Atmospheric and Geospace Sciences
AMIP	Atmospheric Model Intercomparison Project
AMS	American Meteorological Society
AMV	Atmospheric Motion Vectors
AOML	NOAA Atlantic Oceanographic and Meteorological Laboratory
ARC	NASA's Ames Research Center
AVAPS	Airborne Vertical Atmospheric Profiling System
BAE	BAE Systems Inc.
BASC	National Academies Board on Atmospheric Sciences and Climate
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCN	Cloud condensation nuclei
CMIP	Coupled Model Intercomparison Project
DA	Data Assimilation
DOD	U.S. Department of Defense
ECMWF	European Centre for Medium-range Weather Forecasts
EOL	NCAR Earth Observing Laboratory
ERT	Earth Resources Technology, Inc.
ESTO	Earth Science and Technology Office
ESA	European Space Agency
ESPC	Earth System Prediction Capability
FAA	Federal Aviation Administration
GEO	Geosynchronous
GEOS-5	Goddard Earth Observing System version 5
GMAO	NASA/GSFC Global Modeling and Assimilation Office
GOES-R	Geostationary Operational Environmental Satellite R-Series Program
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GSFC	NASA's Goddard Space Flight Center
GV	NSF/NCAR Gulfstream-V (GV) aircraft
HIAPER	GV High-performance Instrumented Airborne Platform for Environmental Research
HPC	High-Performance Computing
HQ	Headquarters
IN	(Cloud) Ice Nuclei
JCSDA	Joint Center for Satellite Data Assimilation
JPL	NASA Jet Propulsion Laboratory

LaRC	NASA Langley Research Center
LEO	Low-Earth Orbit
LIDAR	Light Detection and Ranging
MERRA	Modern Era Reanalysis for Research and Applications
MJO	Madden Julian Oscillation
MSFC	NASA Marshall Space Flight Center
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	NOAA/NWS National Centers for Environmental Prediction
NESDIS	NOAA National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NWP	Numerical Weather Prediction
NWS	National Weather Service
O2R	operation to research
OAR	NOAA's Office of Oceanic and Atmospheric Research
OFCM	Office of the Federal Coordinator for Meteorology
ONR	U.S. Navy Office of Naval Research
OSSE	Observing System Simulation Experiment
PBL	Planetary boundary layer
RADAR	Radio Detection and Ranging
RO	Radio Occultation
R2O	Research to Operation
WDR	Weather Data Record

National Aeronautics and Space Administration

NASA Headquarters
300 E Street SW
Washington, DC 20546

www.nasa.gov

NP-2015-07-1956-HQ