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To: The Administration of the 46th President of the United States
The Members of the 117th Congress

Recommended Research and Education Priorities for the Federal Investment in the Academic Atmospheric, Earth, and Related Sciences

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The University Corporation for Atmospheric Research (UCAR), representing 120 member colleges and universities, respectfully submits this white paper recommending a set of research priorities for the academic atmospheric, Earth, and related sciences to the new Administration and the 117th Congress.

A focused investment of federal resources in the atmospheric, Earth, and related sciences will make significant contributions toward meeting important societal concerns including: protection of American lives and property; expansion of new economic opportunities; enhancement of national security; and strengthening U.S. leadership in research and development. This white paper focuses on the challenges and importance of investing in the following priority areas:

- Weather;
- Water;
- Climate;
- Air Quality;
- Space Weather; and
- Education & Training

These recommendations relate directly to the federal agencies for which the atmospheric, Earth, and related sciences play an important role in their various missions. These agencies include the Office of Science and Technology Policy (OSTP); the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), the Department of Agriculture (USDA), the Federal Aviation Administration (FAA); the Department of Defense (DOD), the Department of Homeland Security (DHS), the Department of the Interior (DOI), the Environmental Protection Agency (EPA), and others.

The recommendations are also consistent with newly enacted bipartisan legislation, including the Weather Research and Forecasting Innovation Act of 2017, the National Integrated Drought Information System Reauthorization Act of 2019, and the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act of

2020, as well as current and past guidance provided by the House and Senate Appropriations Committees.

This UCAR white paper also supports and builds on the September 2020 American Meteorological Society (AMS) policy statement: Priorities for a New Decade: Weather, Water, and Climate. In that statement, the AMS outlined the need for such priorities as the continued development of people; research; observing capabilities and computing infrastructure; scientific advances for societal benefit; and the evolving partnerships among the public, private, and academic sectors of the weather, water, and climate enterprise.

Strategic investments will help the nation enter a new age of prediction, based on an increasingly sophisticated understanding of the interconnected nature of the Earth system. By investigating the atmospheric, ocean, land, and cryosphere as a coupled system, scientists are laying the groundwork for more accurate predictions across time and space scales, helping society prepare for threats ranging from lightning strikes that may affect a military test range within hours to unusually cold and wet weather patterns that may affect a continental region over the next decade. These advances rely on three research components that are foundational to Earth system science: detailed space-based and ground-based ***observations***; computer ***models*** that simulate complex processes; and ***data assimilation*** that enables scientists to incorporate observational data into the models. Strengthening the nation's forecasting capabilities will require appropriate investments into each of these foundational technologies. In evaluating the effectiveness and resource needs of federal efforts in each of these research components, three questions need to be asked:

1) Observations - what gaps exist in the current system of observations that are impediments to achieving greater predictive capability, and what the relevant decision trades that are needed between ground- and space-based platforms to overcome these gaps?

2) Data assimilation - what systems are used and needed to assimilate data (inclusive of high-performance computing) and what percentage of existing high-quality data are assimilated into key decision support systems with demonstrable impact?

3) Models - how reliable are existing predictive models, and are the shortcomings in models (e.g., US vs. European weather models) and related steps needed to improve them within a four-year period identified in a way that can be measured by the research community, policy makers, and the public?

Background Information

UCAR, based in Boulder, Colorado, is a nonprofit consortium of 120 North American member colleges and universities focused on research and training in the atmospheric, Earth, and related sciences. It was founded in 1960 to manage the National Center for Atmospheric Research (NCAR) on behalf of the NSF. Today UCAR's mission is to empower its member institutions and NCAR by: promoting research excellence, developing fruitful collaborations, managing unique resources, creating novel capabilities, building critical applications, expanding educational opportunities, and engaging in effective advocacy.

NCAR was established as a center of excellence for research and education in the atmospheric sciences and to provide research support, facilities, and services for the atmospheric, Earth, and related sciences and the wider geosciences community. NCAR is designated as an NSF Federally Funded Research and Development Center (FFRDC) with approximately 750 full--time equivalent staff. The NCAR mission is to understand the behavior of the atmosphere, Earth, and related systems; to support, enhance, and extend the capabilities of the university community and the broader science community, nationally and internationally; and to foster the transfer of knowledge and technology for the betterment of life on Earth. This mission is accomplished through scientific research; the development, improvement, and operation of a number of facilities; and education and outreach programs.

In collaboration with the university research and education community, NCAR focuses on fundamental research aimed at improving our ability to predict meteorological, air quality, and space weather hazards and increasing our understanding of the variability in and changes to Earth's climate system at regional and global scales. These research themes are enabled by NCAR–operated facilities such as unique aircraft; petascale supercomputing capabilities; and state-of-the-art community models. Partnerships with researchers in complementary fields, such as hydrology, cryospheric science, oceanography, terrestrial biology, public health, and social sciences, broaden NCAR's activities beyond the traditional atmospheric, Earth, and related sciences. The 2020-2024 NCAR Strategic Plan emphasizes the importance of advancing fundamental research that enables actionable Earth system science discovery in ways that will enhance societal outcomes, especially in the areas of human health and well-being, critical infrastructure, protection of lives and property, and scientifically sound responses to climate change.

UCAR, as the manager of NCAR for NSF, is responsible for:

- Planning, executing, staffing, and managing the NCAR program;
- Providing and maintaining advanced observational, computational, and modeling facilities and services to support the research and education community;
- Operating and maintaining the NCAR buildings and facilities, and developing and incorporating new facilities, as appropriate;
- Recruiting, developing, and retaining a highly competent and diverse staff;
- Planning for and implementing future initiatives in partnership with UCAR member institutions and the research and education community; and
- Overseeing and sustaining an innovative and vigorous program of basic and applied research in support of the atmospheric, Earth, and related sciences.

UCAR believes that in order for the research and education community to contribute both the knowledge and human resources needed by society, it is essential that the NSF, NOAA, NASA, and the other related mission agencies receive priority support for their research and education activities as well as the continued improvement of operational programs. In addition, the agencies should be commended for, and encouraged to build on, their highly collaborative relationships not only within the federal enterprise, but also with the academic and private sectors.

UCAR provides important scientific support not only for the university-based atmospheric, Earth, and related sciences community, but also for the agencies with missions that require research, data analysis and management, and training in these disciplines. UCAR endorses a set of core values to ensure the nation's research and education enterprise remains strong, vital, and productive. These values include:

- The dependence on merit review and the pursuit of objectivity in research;
- Broad and inclusive federal investment in research and education to ensure success in the endeavors discussed below; and
- The responsibility of the research and education community to enable the beneficial use of scientific discovery by society.

Recommended Research and Education Priorities for the Academic Atmospheric, Earth, and Related Sciences

WEATHER: Accurate weather forecasts are critical in providing important information for short-term and longer-term decision making as well as giving early warnings of impending severe weather. The goal of weather prediction is to provide timely and accurate information that will serve to reduce weather-related losses, protect life and property, improve public health and safety, support economic prosperity and national security, and improve the quality of life for all Americans.

The benefit of investing to improve public weather forecasts and warnings is substantial: the estimated annualized benefit is about $31.5 billion, compared to the $5 billion spent annually by the federal government for generating the baseline information.

Given the continuing evolution of the weather enterprise — particularly the significant growth of the private sector's ability to provide unique weather-related products and services, and the demise of some observing capabilities — there is a real need for one or more forums that enable public-private sector strategic planning. A National Academies decadal survey related to weather would represent a particularly valuable contribution, enabling the US to establish a prioritized roadmap for advances in research and forecasting to provide maximum benefits to society. Such a survey, involving representatives of the public and private sectors, could develop a strategic set of federal (domestic- and defense-related) weather research and operational priorities that would be useful for decision and policy makers in an era of constrained resources. NOAA's proposed Earth Prediction Innovation Center also offers the promise of advancing the nation's weather forecasting capabilities by fostering greater coordination among researchers and forecasters.

Improvements in short-term and seasonal forecasting would benefit society in many ways beyond being better prepared for severe weather events. Use of weather information will allow for better options in the decision-making of virtually every economic sector from construction to transportation. It would lower operational costs for the commercial airline industry, increase the productivity of solar and wind energy, and enable wholesalers and retailers to oversee supply chains more efficiently. Improved seasonal forecasts would also be of value to the agricultural sector of the economy, enabling farmers, suppliers, and others to take full advantage of predicted beneficial weather conditions as well as to prepare for the likelihood of adverse weather conditions such as drought or flooding. The development of new artificial intelligence and machine learning techniques, coupled with more powerful supercomputing resources, have the potential to lead to improved forecasts of hazardous events ranging from hail storms to hurricanes.

The United States should unambiguously lead in operational numerical weather prediction and Earth observing capabilities. By many measures, however, our capabilities lag behind our international competitors. This suggests the U.S. could be mitigating the economic, national security, and public safety implications of severe weather more effectively.

The university community is working to develop a better fundamental understanding of the integration of Earth system sciences as well as better models (and the computing capabilities needed to use such models) to simulate local-, regional-, national-, and global-scale conditions that impact severe storm development. In addition, the university community strongly supports the need for the sophisticated integration of the social sciences in the design and execution of future weather and climate research activities as well as the dissemination of weather and climate relevant information. Such research will enable better predictions of, and responses to, storms and other forms of severe weather in ways that can reduce loss of life and property and limit economic damage to areas experiencing severe weather.

Fundamental research and training, via support provided by the NSF and, to a more limited extent, by other federal agencies, underpins any meaningful effort to improve the quality of weather forecasts. This includes such areas as: studies of the physics, chemistry, and dynamics of Earth's upper and lower atmosphere and its space environment; research in weather and climate processes and variations; and research to understand the natural global cycles of gases and particles in Earth's atmosphere.

Given the continuing evolution of the weather enterprise – particularly the significant growth of the private sector's ability to provide unique weather-related products and services, and the demise of some observing capabilities – there is a real need for one or more forums that enable public-private sector strategic planning. A valuable contribution would be a National Academies' decadal survey related to weather, involving representatives of the public and private sectors. Such a survey could develop a prioritized set of federal (domestic- and defense-related) research and operational priorities for weather research and forecasting that should be useful for decision and policy makers in an era of constrained resources. One illustrative example of what such a study could include is examining how best to evaluate the resource trade space for observations across multiple agencies and various research and operational ground- and space-based platforms to improve the accuracy of weather forecasting. NOAA's proposed Earth

Prediction Innovation Center also offers the promise of advancing the nation's weather forecasting capabilities by fostering greater coordination among researchers and forecasters.

<u>WATER</u>: Water challenges are confronting communities across the United States and the world, affecting billions of people and costing billions of dollars in damages. These challenges are particularly problematic in predominantly poor, minority, and rural communities, where water inequality can go hand-in-hand with socioeconomic inequality. Events in recent years, including record-breaking drought and associated wildfires in the West, severe flooding in the Great Plains and Southeast, and reports of lead-contaminated drinking water in several parts of the country, have focused attention on the state of our nation's water quality, resources, and infrastructure. Changing climate conditions are exacerbating these water issues. Conditions related to water quality, energy production, water resource management, and water infrastructure are even more challenging in developing countries. Accordingly, we must work together to build a sustainable water future — one in which everyone has access to the safe, clean, and affordable water they need, when and where they need it.

Weather and climate models are fundamental for understanding Earth's water cycle and issues related to water availability, quality, resource management, energy production, flooding, and drought. One focus of water research is to reduce uncertainty through improved understanding and integration of the water cycle in weather and climate models. Another research component is the examination of the impact of climate change on water systems and determination of potential effects on water management policy.

Research support is needed in areas related to improving modeling that will deliver more timely and detailed flooding forecasts. Water managers and planners need accurate estimates of snowpack and streamflow in ways that will provide more information about spring runoff, flooding, and municipal water supply availability. Scientific research is needed to improve flood forecasts and anticipate unusually wet or dry conditions far in advance. The development of reliable drought forecasting a year or more in advance would give the government and private sector the time and information to prepare accordingly. This is particularly important in regions such as the Southwest, where changing precipitation patterns and growing populations are making communities increasingly vulnerable to water shortages and drought.

A complete understanding of the water system requires an approach that extends beyond the atmosphere to include links among Earth's water system climate change, land use, population demographics, and ecosystems. For example, some regions of the country, like the Upper Missouri River Basin, have begun to implement through the U.S. Army Corps of Engineers a plan to improve flood monitoring. Such an effort should be reviewed to prioritize future investments so it can be considered as a new model for flood forecast improvements in all regions of the U.S. based upon risk and scientific need.

<u>CLIMATE</u>: Climate change is already having major impacts in the U.S. and across the world via heat waves, extended droughts, wildfires, migration of disease-carrying insects and other

organisms, coastal flooding, and other events. The warming atmosphere is leading to more extreme rain and snow events, and the warming oceans are fueling increasingly powerful hurricanes. Effects that scientists have long predicted would result from global climate change are now occurring: accelerated sea level rise, shrinking glaciers, shifting plant and animal ranges, and changes in precipitation patterns.

Global temperatures repeatedly set new record highs in the past 2010s, with additional warming expected in the coming decades because of greenhouse gases already in the atmosphere as well as future emissions. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat- trapping gases emitted globally, and how sensitive Earth's climate is to those emissions.

Rising temperatures have not been, and will not be, uniform across the country or throughout the world because human-induced warming is superimposed on a naturally varying climate. Instead they will impact different regions in different ways. Frost-free and growing seasons will lengthen, affecting worldwide agricultural food production. The Arctic is warming rapidly, with major implications for local communities, ecosystems, and geopolitics. Ocean warming and acidification is damaging corals and other marine organisms, threatening entire ecosystems.

Changes in precipitation patterns will continue. For example, more winter and spring precipitation is projected for the northern United States, and less for the Southwest, over the course of this century. More extensive droughts and heat waves are expected to occur, and severe storms, such as hurricanes and typhoons, are expected to become more intense. Sea levels could increase by several feet depending on the location, with coastal flooding already affecting many communities. The intensifying impacts can spark regional conflict and instability in many regions of the world, posing particular risks to those who are most impoverished. Many of the trends associated with climate change have national security implications.

As a public policy issue, global climate change presents a number of key issues, as the societal consequences of climate change are highly uncertain but include the potential for major and far-reaching impacts. Global climate change risk management approaches generally fall into the following categories: mitigation, adaptation, geoengineering or climate engineering, and knowledge-base expansion. Research to understand more about the climate system can help support proactive risk management. Policy solutions in the past have not considered with any level of observational detail the need to independently verify and validate greenhouse gas measurements. Much like the need for research in the observations needed for nuclear treaty verification, a similar need exists regarding the observations required from a policy perspective for greenhouse gas treaties.

Comprehensive global climate change risk management includes a combination of policy responses. However, policy choices necessarily integrate both objective information about the climate system and our relationship with it, and subjective value judgments such as whether we are more averse to the risks of changes in climate or the policy responses, the ways we assess issues of fairness among nations and peoples, and the consideration we give to cultural heritage or nonhuman species. This creates a complex and often contentious risk management challenge, even as many nations focus on the goal of preventing average global temperatures from increasing by more than 2 degrees Celsius.

Understanding global climate change is critical to this country's and the world's welfare. Fundamental use-inspired research, made possible by cutting-edge tools for collecting and analyzing data, can provide the knowledge that governments, businesses, and communities need as they address the climate-related changes that pose growing risks to life, property, natural resources, and the economy. Research goals that would more effectively inform the response to climate change include better understanding the interacting physical, chemical, biological, and societal components of the Earth system, the vulnerability and resilience of its natural and human dimensions, and the potential to use technology to remove carbon from the atmosphere or artificially cool the planet. Such research depends on sustained programmatic investments in multidisciplinary observations, process studies, and modeling. These foundational components of scientific inquiry require their own expertise, infrastructure, and planning horizons, but they ultimately work together to produce a more comprehensive and integrated understanding of global change.

<u>AIR QUALITY</u>: Air quality affects broad sectors of society, from human health to crop yields to enjoyment of our national parks. Studies have shown that more than 100,000 people in the U.S. die each year due to outdoor air pollution, and the annual cost to the nation is estimated at nearly $150 billion due to disease, missed work, and damage to crops and forests. Particulate matter and ozone are major contributors to unhealthy air, often triggering air quality alerts. Scientists are improving computer models to better analyze and track pollutants, which may travel thousands of miles in the atmosphere. They are developing detailed air quality forecasts that would provide decision-making information to local officials and vulnerable residents days in advance.

Additional work is needed within the academic research community regarding the development of modeling tools to characterize air quality and predict exposures at local to urban scales, regional to continental scales, and global to hemispheric scales; and the linkage of air modeling tools with modeling tools for other media (e.g. weather) and development of an integrated multimedia modeling system. In addition, physical and health scientists are working on analyzing emissions from wildfires to better understand the evolution, movement, and health implications of pollutants in the atmosphere. Improved observations and numerical modeling both play an important role in advancing our understanding of air pollution and ultimately leading to more accurate and detailed forecasts.

<u>SPACE WEATHER</u>: Space weather can disrupt vital technologies — both space-based as well as ground-based — that form the backbone of this country's economic vitality and national security, including satellite and airline operations, communications networks, navigation systems, and the electric power grid. Effective actions to prepare for space weather events require a better understanding of solar storms and the Sun-Earth connection. Benchmarks will help government and industry assess the vulnerability of critical infrastructure, establish

decision points and thresholds for action, understand risk, and provide points of reference to enable mitigation procedures and practices and to enhance response and recovery planning.

Opportunity exists to improve the fundamental understanding of space weather and increase the accuracy, reliability, and timeliness of space-weather observations and forecasts (and related products and services). The underpinning science and observations will help drive advances in modeling capability and improve the quality of space-weather products and services. A better capacity to develop and transition the latest scientific and technological advances into space weather operations centers will enable an improved rate of forecast improvement.

To advance space weather capabilities, the bipartisan PROSWIFT Act, signed into law by President Trump in 2020, laid out a clear road map for bringing together expertise in government, the private sector, and academia to address space weather research and observational needs. It is essential that relevant federal agencies coordinate their actions and their assets to improve, and design appropriately, observation systems. The nation needs a mix of assets: space-based measurements that provide the coverage necessary for observing space weather hazards, some of which cannot be detected from the ground, and ground-based measurements that provide more extensive spatial coverage. Policy makers should focus on two primary emphases: a) improving our understanding of the physics of the Sun and how it creates major solar events; and b) determining how best to increase continuous observations of the Sun to improve warning times. A goal for both of the above would be to go from minutes to days of warning time for space weather hazards.

EDUCATION & TRAINING: The success of the research challenges above is dependent on a science, technology, engineering, and mathematics education system that produces a diverse and skilled workforce, as well as a well-informed public that has access to the ideas and tools of science and engineering. STEM education — at all levels, from K-12 to undergraduates and postgraduates — will contribute to the enhanced quality of life of all people and the health, prosperity, welfare, and security of the nation. Investments in universities and their research programs are especially important in the wake of financial losses during the COVID-19 pandemic.

The goals for this nation's STEM education activities should include: preparing more Americans for STEM careers in the Earth system sciences and beyond; training in new research frontiers such as machine learning; developing innovative teaching techniques and community engagement through new technologies such as augmented reality/virtual reality; establishing partnerships among academia, the private sector, and government to train the next generation of scientists and engineers through apprenticeship models; and ensuring that STEM education incorporates best practices for diversity, equity, and inclusion. These goals will increase the technological, scientific, and quantitative literacy of all Americans so they can maintain a high level of productivity in an increasingly technological society; and they will also broaden participation across demographics, geographic regions, types of institutions, and disciplines, thereby closing achievement gaps in all STEM fields.