Ensuring Robust and Successful Weather Forecasting

Statement of

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before the

Science, Space, and Technology Committee
Environment Subcommittee

for the hearing

Protecting Lives and Property: Harnessing Innovative Technologies to Enhance Weather Forecasting

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Chairman Franklin, Ranking Member Amo, and members of the subcommittee, thank you for the opportunity to testify today on the very important matter of improving weather forecasts through the development of new technologies and the use of diverse data sources. It is my understanding that this hearing is intended to support deliberations on the *''Weather Research and Forecasting Innovation Reauthorization Act of 2025."* I greatly appreciate the work of this committee and its bipartisan efforts to examine the capabilities and opportunities to improve weather forecasting to serve the interests of the Nation. In addition, it is a privilege to be here with representatives from the private sector, academia, and state office who together strive to develop capabilities, educate people and communities, and serve critical interests in the weather forecasting domain for the good of the American people, and for the good of the world.

Weather affects so many aspects of our personal and collective daily lives, and accurate information benefits us in a myriad of ways. From planning our days to enabling us to prepare and successfully manage severe weather events, natural disasters, seasonal change, and more, the benefits of a robust understanding touch all aspects of our lives. At the individual level, these benefits may be in support of our health, comfort, safety, and well-being, and can be lifesaving. At the state, regional, and national level, these interests encompass economic prosperity, national security, public safety, and more.

Accurate forecasting is at the core of addressing weather-related challenges and seizing related opportunities. I am therefore grateful to this subcommittee and others in Congress for their strong bipartisan support of facilitating improvements to these capabilities and your efforts to pass the *Weather Act Reauthorization Act of 2025*, to build on the successes of the original "*Weather Research and Forecasting Innovation Act of 2017."* I am also grateful for the opportunity to participate in this hearing today.

New and innovative observing technologies provide important opportunities for understanding and improving weather forecasts. I know that some of my fellow witnesses will share their perspectives on some of those capabilities, and I will highlight a few myself. It is important, however, that there also be some discussion of the critical broader dimensions of a successful weather enterprise. Specifically, I will address how the integration of a range of data sources, both new and traditional, as well as the research necessary to develop and maintain successful weather prediction capabilities, greatly enhance the accuracy, timeliness, and effectiveness of weather forecasting efforts.

The research that underpins forecasting is critical. That is why I am very happy to see research explicitly called out in the *Weather Act Reauthorization Act of 2025*. While the U.S. weather enterprise has made great strides over the years in improving forecast accuracy and extending lead times, those strides were a result of robust fundamental research investments to develop and apply a comprehensive understanding of the physics and chemistry that drive weather, as well as investments in computational modeling, data processing and management, *and* advancements in observational capabilities. Moreover, to understand the processes and phenomena that influence today's weather, we require an understanding of the backdrop against which that weather occurs. For example, as regions warm (or cool) with time, the energy that drives processes and parameters, such as winds, evaporation, atmospheric moisture, surface conditions, cloud cover, precipitation, etc. are impacted by those changes. As such, to fully understand how weather systems will develop and behave, it is important to understand the trends in the variables that affect those systems and on which short-term variability is overlaid. Toward that end, essential research and observations that must be continually supported include not only a focus on the physics of weather-related processes at time scales from minutes to seasons, but also their evolution over periods from years to decades.

Observations for Monitoring and Prediction

Observations produce the fundamental data that helps us understand current conditions, the evolution of those conditions, and interactions of various components of weather systems so that we can make informed predictions. From surface-based instrumentation, airborne capabilities and space-based systems, the suite of observational capabilities anchors models and informs forecasts in powerful ways.

Balloon-mounted radiosondes, which provide vertical profiles of temperature, pressure, humidity, windspeed and wind direction have a history that dates back a century and have been critical to weather forecasting for about as long. The U.S. has 92 upper-air stations where these balloons are launched, out of about 1,300 worldwide (Figure 1). These data, historically collected twice daily at the same time each day, feed into forecast models ensuring that they capture the true physical conditions in the atmosphere at precise locations. While the focus of this hearing is on new technologies, rather than century-old capabilities, it is important to keep in mind that the old technologies play a key role as well and are an indispensable part of a robust observational portfolio.

On a more technological front, doppler radar capabilities take advantage of the fact that radar waves are reflected by droplets in the atmosphere, providing information about their size and quantity as well as the wind speed and direction. From this information we get insight into storm evolution, severity and path. The current weather radar system, known as NEXRAD, is a network of 159 high-resolution S-band radars that are jointly operated by NOAA, the United States Air Force, and the Federal Aviation Administration (FAA). They serve the missions of all three organizations by providing critical measurements of storm conditions (Locations are shown in Figure 2). The NEXRAD system has evolved over the last 30 years with continual improvements along the way, such as the introduction of dual polarization radar, and increased resolution and sampling. Looking forward, it is expected that the transition from mechanical scanning with a dish, to phased array technology in which an array of thousands of elements on a flat antenna can scan electronically, will reduce the scan time from 4-5 minutes per scan to about 60 seconds per scan. Moreover, the phased array approach will have an adaptive capability that allows for targeted observations during severe weather events. This exciting new and innovative capability will greatly improve weather forecasting, particularly in the case of intense storms, with their greater observation rate and targeted viewing capability.

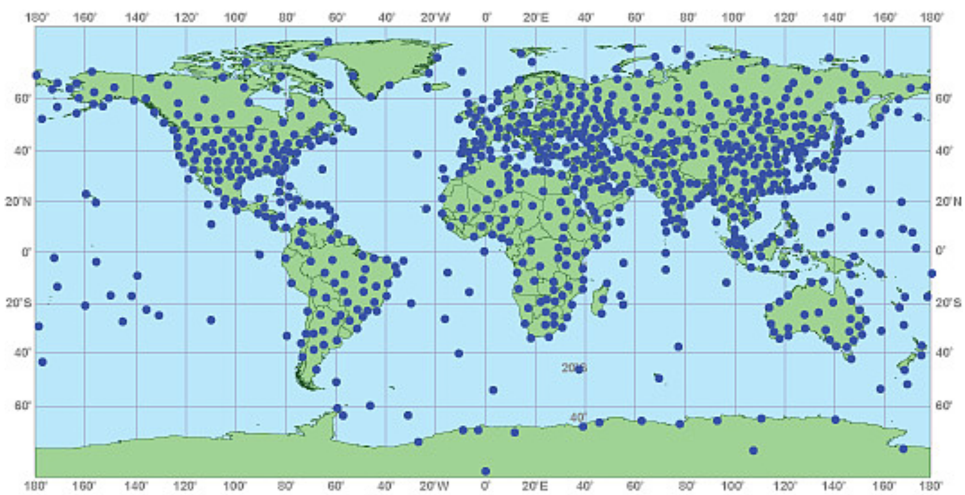


Figure 1: Locations of radiosonde observations worldwide. 92 of the world's approximately 1300 stations are in the United States (https://www.noaa.gov/jetstream/upperair/radiosondes).

Similar to land-based measurements, direct measurements of temperature, humidity and winds from aircraft in advance of and during hurricanes and storms, have long informed models to produce accurate assessments and predictions of strength, rainfall, and trajectories. Like radiosondes (but deployed from above), dropsondes are released from aircraft providing detailed in situ measurements as they fall to the sea. Winds are detected by doppler radar in the aircraft, allowing detailed mapping of wind speed and direction (Figure 3, left side). This information allows for accurate characterization of the storm and informs predictions of strength, magnitude, and precipitation. These types of measurements are indispensable for managing the threats of severe storms and mitigating the damage.

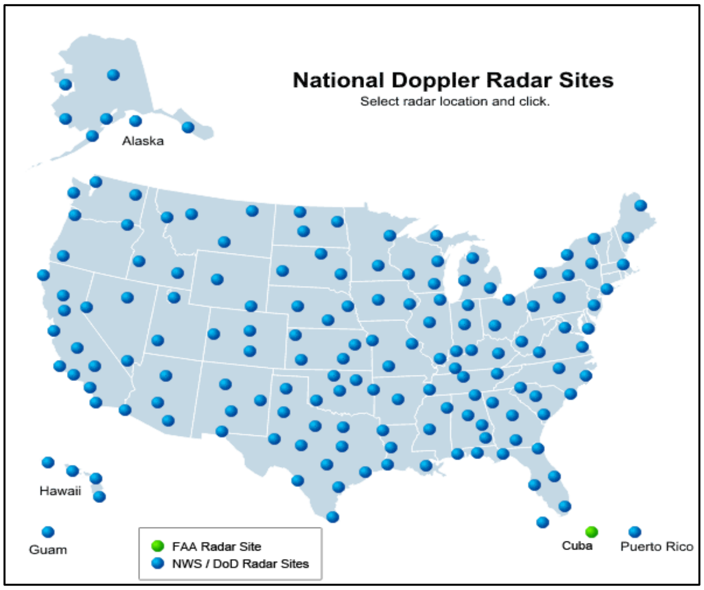
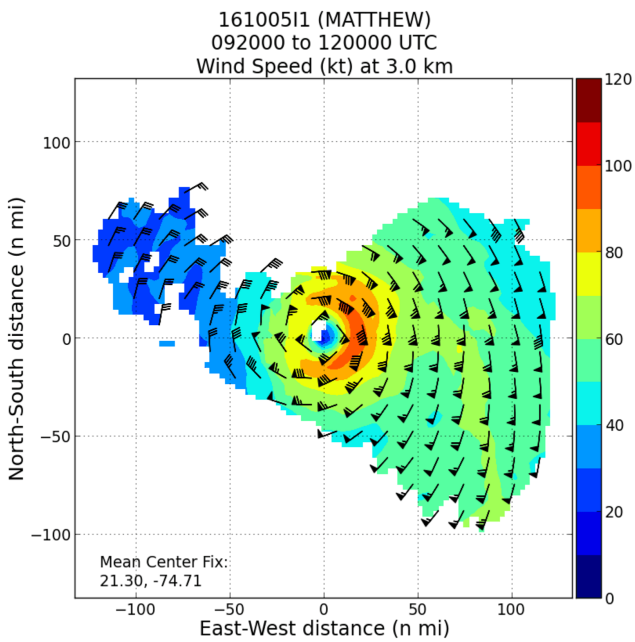


Figure 2: National Doppler radar sites (https://www.weather.gov/grb/radar_update)



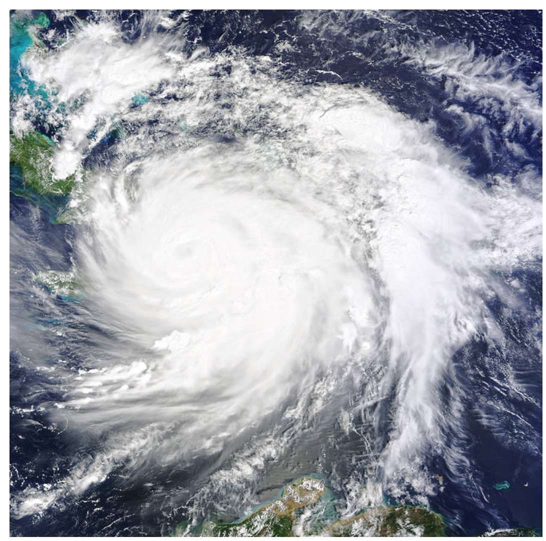


Figure 3: Left: Aircraft tail doppler-derived winds during Hurricane Matthew in 2016 (AOML, 2016); Right: Natural color image acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite (NASA Goddard, 2016). While the MODIS image clearly shows the extent of the hurricane, the bands and the cloud cover, the doppler image shows the strength and windspeed and provides precipitation. Together they provide a comprehensive depiction of the hurricane structure, extent, precipitation, winds and trajectory.

Recently emerging airborne, surface borne, and subsurface drones technologies can also offer capabilities that are a powerful complement to aircraft observations. They can provide valuable information on the energy and moisture exchanges at the surface, subsurface, and in the lower atmosphere. Their deployment and incorporation into operational weather forecasting systems is still not routine, but they have demonstrated their value and tremendous potential. To realize that full value, however, continued investment in research, development, and deployment must be made.

Finally, satellite observations have been a powerful and foundational element of a fully capable observing strategy. Since the launch of the first Television Infrared Observation Satellite (TIROS) satellite by NASA in 1960, the value of the space-based perspective for understanding and predicting weather has been understood. Today, NOAA's fleet of weather satellites, both geostationary and polar-orbiting, make foundational observations that provide the perspective at a scale that is necessary to truly understand the development and dynamic characteristics of weather systems and how they fit into a broader context. For example, in the case of hurricanes, satellites observe the genesis, evolution, movement, structure, and dissipation of storms complementing – and informing – direct airborne measurements of wind speed, moisture, precipitation and temperatures. These space-based observations provide large-scale quantitative information on the trajectories, the fuel from which they get their energy (by deriving ocean heat uptake from sea surface temperatures), cloud evolution and precipitation over large spatial scales. In so doing, they provide a means of assessing and predicting the trajectories and impacts as they develop, move, and dissipate.

The next generation of NOAA satellites will employ a mix of existing and new operational capabilities. The GeoXO satellites were intended to provide continuous observations over the east, west, and central U.S. of:

- Lightning to support analysis of severe storms and prediction of hurricane intensity, as well as inform responses to wildfires, estimate precipitation, and mitigate aviation hazards. This is a continuation of capabilities on the GOES-R series,
- Hyperspectral infrared atmospheric soundings providing continuous information on the vertical distribution of winds, temperature, and moisture in the atmosphere. A major advance here is that this will be accomplished using over 1550 spectral bands, as opposed to the 18 bands on previous geostationary sounders,
- An imaging capability that includes improved resolution and observations of water vapor, particularly in the lower troposphere. These capabilities will enable insight into severe weather, detection and monitoring of wildfires, improved hurricane tracking and forecasting, and detection and tracking of environmental hazards, such as smoke, aerosols, and volcanic ash,
- Atmospheric composition, including pollutants, at hourly intervals, as opposed to the current once-daily observations, and
- More sophisticated ocean color observations to support economic, health, safety, and government interests.

The administration's 2026 budget proposal seeks to eliminate the sensors that would carry out the last two bullets, as well as eliminate the satellite over the central U.S. A loss of these sensors would diminish our capacity to understand critical aspects of our environment in ways that would reduce our weather forecasting ability and adversely impact human health and well-being.

The next generation polar orbiting satellites is the Near-Earth Orbit Network (NEON) system, the first of which is expected to launch later this decade with the series expected to continue into the 2030s and 2040s. NEON is intended to provide quick deployment of small to medium sized satellites, providing a network of Earth observing satellites to support weather forecasting and disaster management. Key observations to be demonstrated on the first NEON satellite will include microwave sounding, which will provide more detailed information on atmospheric temperature and water vapor from Earth's surface to the upper atmosphere, in both cloudy and cloud-free conditions. The NEON program is intended to create a more agile partner-oriented capability than currently exists.

Satellite observations of the Arctic, made by polar orbiting satellites, provide important insights into the state and evolution of polar sea ice and land ice cover. While geographically removed from much of the U.S., Arctic conditions have direct implications for weather prediction – both near and long term. This is because the ice provides an important boundary condition for high-latitude meteorological processes, which can be fed into models to understand how they affect processes at lower latitudes in the United States (Figure 4). In addition to the meteorological applications, understanding the evolution of the Arctic sea ice provides basic information on the navigability of the Arctic and the potential for resource extraction, both of which have commercial and strategic implications. Further, as the Arctic becomes more navigable and operations increase, accurate forecasts in these difficult to sample regions will become increasingly important. Unfortunately, the data stream from the primary sensor that provides information on sea ice extent, concentration, and age, which for decades has been provided by instruments on the Defense Meteorological Satellite Program (DMSP) will be halted at the end of this month, reducing our ability to track these important variables. Other satellite capabilities will fill the gap to some degree, but they will leave questions about the ice conditions and their interaction with climate and weather systems that have been so well informed by the continuity of observations and the long-standing time series.

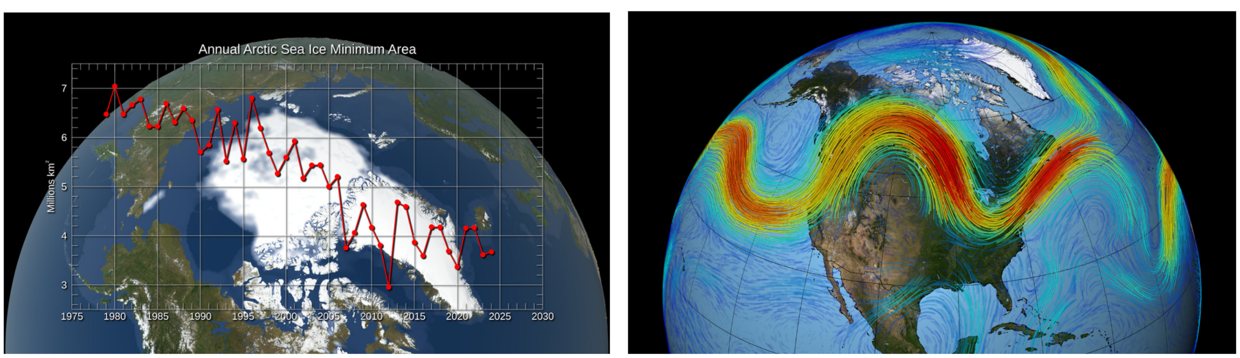


Figure 4: Left: Arctic minimum sea ice extent from 1979-2024, showing a declining trend in ice cover over the last 4.5 decades resulting in a significantly greater exposure of ocean water to the atmosphere. Right: Atmospheric circulation patterns showing the linkage between the high-latitude regions and the United States. Images courtesy of NASA (Right and left images are (https://svs.gsfc.nasa.gov/5395/ and (https://svs.gsfc.nasa.gov/3864 respectively.).

It is important to keep in mind that with the focus of this hearing being on new technologies, satellites have always been a product of new and emerging technologies. The suite of NOAA's planned missions incorporates those capabilities and pushes operational observational limits. Sounding profiles and capturing the evolution of key variables is essential for supporting robust prediction.

The space-based observing technologies that are essential for NOAA to successfully carry out its mission usually have their roots in research and technology and mission investments at NASA, which produces the state-of-the-art observing capabilities. Moreover, the basic research that is done with data from NASA satellites provides fundamental insights into the physics and chemistry that impact weather, which in turn lead to improved weather forecasts. The highest priorities of these observations were identified through robust deliberation by experts during the National Academy of Sciences Earth Science and Applications from Space 2017 Decadal Survey (NAS, 2018). The results of this two-year study were used to inform NASA's investments in its Earth System Science portfolio, much of which focused on understanding weather processes and the phenomena that drive weather on scales that could not be observed in any other way.

The highest priority of these in the weather domain were the nature, distribution, and movement of aerosols, the processes that drive cloud formation and convection, measurement of winds and more; there is a detailed list of the highest priority such observations in Appendix A. This list was developed with an eye toward ultimately improving weather forecasts and our understanding of weather phenomena. Those observations deemed most important formed the basis of NASA's Atmosphere Observing System (AOS), which has been a focus of NASA Earth Science Investments for the last several years with planned launches around the end of this decade. The administration's budget proposal for 2026 seeks to eliminate, or drastically reduce, many of these missions and associated research efforts within the Earth Science Division of NASA's Science Mission Directorate. If adopted by Congress, such a funding paradigm will take years or even decades to recover from, preventing our understanding of weather processes from evolving, and inhibiting our ability in the future to improve predictions.

Observations for Understanding Processes

The observational capabilities listed above are aimed at directly informing weather forecasts. In essence, they provide information about the state of the system and its evolution, so that accurate predictions can be made. There is another class of observations that are crucial for longer term improvements in that they provide the insight and knowledge about processes that enable us to understand the physics necessary to develop good predictive capabilities. These observations include field campaigns, where direct and detailed measurements of meteorological processes and phenomena are made. They also include satellite observations that are not intended for forecast purposes (yet), but rather they support an understanding of weather phenomena. The space-based observations identified in Appendix A fall directly into this category in that they advance fundamental knowledge that will ultimately improve weather forecasts. Developing the capabilities listed would significantly advance our understanding of weather and weather-related processes.

Complementary Observations for Determining Impacts of Weather Events

While the observations described above are essential for developing accurate weather forecasts, anticipating the full impact of weather events and determining how to respond requires additional considerations. Chief among these are ancillary environmental conditions that impact how weather events interact with the landscape and affect communities. For example, although the severity of a flood is primarily determined by the amount and rate of rainfall, the amount of runoff is inextricably linked to the ground conditions such as soil permeability, moisture capacity, topography, and vegetation cover. As such, observations that track soil moisture, drought, and vegetation provide critical information for flood vulnerability. In addition, snowpack water content and the rate of melt have implications for flood potential as well, thus observations of the amount of water stored as snow, and the meteorological conditions that cause melt are also important variables to observe. These observational needs are best met with a combination of ground-based, airborne, and satellite observations.

As with floods, fire is a tremendously impactful hazard that is directly tied to meteorological conditions. On a personal note, my neighborhood and 1100 nearby homes burned during Colorado's 2021 Marshall Fire, the most destructive and costly fire in Colorado's history. When I was forced to evacuate my home (with my very scared daughter and coughing dog) two things stood out to me. The first was the intense wind, which fanned the flames and caused the fire's rapid spread. The second was how dry the vegetation was as I evacuated. This dry vegetation provided fuel, which carried the fire farther and more rapidly than it would have otherwise. The date was December 30; the fall had been dry, and it had not yet snowed that winter. My point is that the impact of the meteorological event that occurred was not just determined by the winds, but also by the dryness of the vegetation. On large scales, land-cover and vegetation health can be monitored by satellites. During the fire, it was possible to monitor the fire burns and locations with near-real-time satellite observations. More importantly, through the use of NOAA's High Resolution Rapid Refresh (HRRR) and its HRRR-Smoke models, NOAA was able to assess fire risk and predict the movement of the fires and the smoke. This information informed evacuations and firefighting strategies.

After the fire, there were, naturally, many questions about indoor air quality and the chemical content of the homes. Through a sophisticated set of measurements of chemicals in the air and soil, in the weeks following the fire, scientists were able to assess the risks to returning residents. Again, this is not directly tied to weather forecasting, but it was an essential part of the recovery from the weather event. Information learned from these observations in the fire has been used as an important resource for recovery from the fires in the Los Angeles area. This is an excellent (though tragic) example of being able to learn from an event in ways that benefit future management of similar challenges.

Another major weather-related hazard is storm surge in coastal regions. Observations of ocean temperatures and ocean topography, coastal topography, coastal bathymetry, regional sea level rise (and its underlying mechanisms) and coastal subsidence are key variables that are necessary to assess the threats to coastal communities and infrastructure. These require observations that are not necessarily meteorological in nature but complement the measurements of winds, ocean circulation, temperature, and humidity enabling successful management of the risks.

Research Informed by Observations

Translating these observations into meaningful outcomes requires, first and foremost, research. This includes research into how the processes function, how they evolve over time, and how they manifest themselves in ways that impact humans. Research is also done in the modeling domains focusing on how to numerically represent the physical processes in accurate reliable ways so their implications can be understood and managed. This is why it is important to preserve the provisions in the *Weather Act* that support research to complement that of the National Weather Service and that are currently carried out through NOAA's Office of Oceanic and Atmospheric Research (OAR) and other line offices, all of which have significant partnerships with the Cooperative Institutes, a network of 16 academic and non-profit research institutions distributed across the nation – from Florida to Maine to Hawaii and Washington – which conduct research that advances NOAA's mission. The need to support these capabilities is called out in the *Weather Act Reauthorization Act of 2025*, and it applies to other aspects of the NOAA budget, which was deliberated last week in the Senate, and will be discussed in the House shortly. It is my hope that these deliberations appropriately recognize the value of these research investments to the nation.

There are other elements beyond observations that ultimately produce successful forecasts. One of these is model development and translation into operational capabilities. Again, this is tied to research. Determining how to numerically describe and capture the processes that affect weather, such that observations can be turned into predictions and usable outputs, requires a detailed understanding of the physics, as well as computational expertise and the ability to translate observations and the evolution of systems into forecasts. The tools that yield success in the prediction domain are grounded in the work that is done far upstream in the process, beginning with the research into the basic physics, which then enables the development of process models that represent, for example, how the moisture and energy fluxes within the atmosphere and between the atmosphere and the surface ultimately shape the weather conditions that follow. The understanding gained from these process studies ultimately is incorporated into research models and then, once sufficiently developed, tested, and validated, feed into operational forecast models.

Much of the research that is done to ultimately improve prediction and predictability is done in various NOAA labs across the country, in partnership with NOAA's Cooperative Institutes. These and other labs and centers conduct the research and develop the capabilities that form the backbone of accurate weather prediction and environmental understanding, for the purposes of protecting lives and property. While the labs, institutes, and their contributions are too many to list here, those in Boulder, Colorado alone (supported by the University of Colorado and Colorado State University) and some of their related research efforts are listed below.

NOAA's Global Systems Laboratory (GSL) develops atmospheric models that improve weather forecast accuracy; decision support tools that deliver weather information for emergency preparedness and disaster response; and expertise that informs wildfire and aviation safety. Among the most relevant aspects of GML's work as it pertains to the *Weather Act Reauthorization Act of 2025* are:

- Development, testing and transition of hourly-updating thunderstorm-scale weather forecast models into NWS operations supporting predictions of severe weather, flooding, winter weather, wildfire smoke, etc.,
- Developing the Unified Forecast System (UFS) applications to support next-generation model systems. This work includes advanced observation assimilation techniques,

developing more precise and accurate physics representation in numerical weather models and coupling of Earth system components (land, atmosphere, ocean, etc.).
- Development of decision support tools for many stakeholders, and
- Managing and operating the Fire Weather Testbed, bringing together emergency managers, land and resource managers, forecasters, and researchers to test new life-saving fire detection and mitigation products and to accelerate their readiness and eventual deployment to operational platforms.

The work at this lab is a major bridge between fundamental research and operational capabilities.

NOAA's Physical Sciences Laboratory (PSL) conducts mission-driven research and applications, in collaboration with partners across the weather enterprise, to:
- Develop and apply models and innovative technologies including AI/ML, to improve predictions on weather-to-seasonal time scales,
- Identify and quantify early warning indicators in atmospheric and oceanic patterns that drive water-related extreme events (such as atmospheric rivers, floods, droughts, wildfires, and heat waves) in the coupled earth system, and
- Transform predictive understanding into advanced capabilities for forecasting U.S. water availability and extremes (too much or too little water), critical for protecting infrastructure and managing water resources for agriculture, energy, and industrial use.

The research capabilities in PSL are currently being applied to the Kerr County, Texas flood. The county was experiencing significant drought, which had an impact on the rate of flooding. By understanding the relationship between the drought conditions and the rate of runoff, we will be better able to understand and quantify the degree to which prolonged drought affects the local and regional vulnerability to severe storms.

NOAA's Chemical Sciences Laboratory (CSL) examines chemical interactions that are essential for accurately characterizing atmospheric composition and predicting meteorological processes. These efforts are important for a variety of weather applications, such as fire weather, air quality forecasting, and aerosol impacts on weather. Among the lab's most directly related efforts are:
- Enabling state-of-science atmospheric chemistry to migrate into operational weather and air quality forecasts,
- Studying the stratosphere's downward influence on weather and evaluation of this influence in NOAA forecast models,
- Advancing prediction of stratospheric ozone amounts, which has the potential also to improve weather forecasts on subseasonal to seasonal timescales,
- Advancing short-term precipitation forecasts through the development of high-resolution numerical models focus on aerosol, cloud, and rain processes, and
- Advancing short-term precipitation forecasts through development of interoperable high-resolution frameworks for simulating a variety of extreme weather phenomena.

NOAA's Global Monitoring Laboratory (GML) has long carried out sustained observations of the Earth's atmospheric gases aerosol particles, clouds, and surface radiation in order to understand their changes, causes of these changes, and the associated implications. Their contributions to the weather forecasting enterprise include:

- Measuring and monitoring trace gases and aerosols for advancing the scientific understanding of their effects on the Earth's radiation budget,
- Making sustained measurements of atmospheric trace gases, which is essential for making accurate predictions of any potential shifts in weather patterns and weather extremes, and
- Deploying sensors and instruments for atmospheric composition measurements on commercial aircraft, other commercial vessels, or uncrewed aircraft, through private-public partnerships. These activities provide a powerful way of scaling up the U.S. observational capacity for comprehensive monitoring of the atmospheric composition both in the troposphere and stratosphere.

Another important area of research is in understanding how people absorb and understand information and how to best deliver that information. The best data, the best analyses and the best forecasts are of limited value unless they are effectively communicated and received by the public and decision makers. Advancing knowledge in determining and employing effective communication strategies that ensure the information informs decisions at the individual, local, regional, and national level is essential for ensuring that the returns on the investment in research, observations, and prediction can be fully realized.

Concluding Remarks

I would like to close by again stating the importance of the *Weather Act Reauthorization Act of 2025* for the good of the nation and people everywhere. And I ask that you continue to support the elements within the Act, including through congressionally directed appropriations that appropriately invest in all necessary capabilities across federal research agencies. For the good of the nation, the safety and well-being of Americans, requires appropriate investments in all the elements contained in the Act as well as complementary research, development, and applications. These include robust new and sustained observational capabilities – as were called out in the Earth Science and Applications from Space 2017 Decadal Survey, the technologies that make them possible, effective modeling efforts, and a sustained healthy research investment to ensure that the understanding of the processes that drive weather and inform its prediction are sufficiently sophisticated and usable. There are many components to each of these aspects, and a healthy enterprise requires investment of the kind called for in the Act.

Finally, I would like to specifically state that to realize the benefits of all of these investments requires people – people to make the observations, people to develop the models, people to develop the understanding of the physics so our models are sophisticated and accurate, people to interpret model results, people to turn those capabilities into continually improving forecasts, and people to communicate to other people the content, meaning, and implications of those predictions. Meaningful return on our nation's investment of financial resources begins with people, it ends with people, and people are a critical part of the enterprise throughout. The best investments we can make, are in people.

I thank you for your time and attention, and I welcome any questions.

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Appendix A

Weather-related observables identified in the National Academy of Sciences Earth Science and Applications from Space 2017 Report (ESAS, 2017). The questions, objectives, and importance were developed and assessed initially by a panel of experts in weather research, and subsequently deliberated by the ESAS Committee

Table 1: Science traceability matrix identifying key science questions and objectives, along with the measurements required to advance those objectives (6 pages).

WEATHER AND AIR QUALITY PANEL

SCIENCE			MEASUREMENT		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches** **Method**
QUESTION W-1. **Planetary Boundary Layer Dynamics.** What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?	**W-1a.** Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts at minutes to subseasonal time scales.	**Most Important**	3D temperature in PBL	Horizontal resolution 20 km, vertical resolution 0.2 km, temporal resolution 3 hr, 0.3 K/0.3 K	Polar/geo IR and microwave sounders, complemented by airborne and surface observations
			3D humidity in PBL	Horizontal resolution 20 km, vertical resolution 0.2 km, temporal resolution 3 hr, 0.3 g/kg	Polar/geo IR and microwave sounders, complemented by airborne and surface observations
			3D horizontal wind vector in PBL	Horizontal resolution 20 km, vertical resolution 0.2 km, temporal resolution 3 hr, 1 m/s	Doppler wind lidar, AMVs from multiangle VIS/IR (occasionally reaching PBL), scatterometer measurements of near-surface winds over ocean
			3D PM component and trace gas (ozone, NO_2) concentrations	Horizontal resolution 5 km, vertical resolution 0.2 km, temporal resolution 2 hr	See approaches listed under W-6 below.
			2D PBL height	Horizontal resolution 20 km, temporal resolution 3 hr, 0.1 km	Lidar (e.g., CALIPSO)
			2D PBL cloud LWP	Horizontal resolution 20 km, 20%	Microwave radiometer
			2D cloud base	Horizontal resolution 20 km, 0.1 km	Lidar
			2D precipitation	Horizontal resolution 10 km, 20%	Passive microwave (e.g., GPM), radar; complemented by rain gauges and radar over land
QUESTION W-2. **Larger Range Environmental Predictions.** How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?	**W-2a.**Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO), including upscale interactions between the large-scale circulation and organization of convection and slowly varying boundary processes to extend the lead time of useful prediction skills by 50% for forecast times of 1 week to 2 months. Advances require improved: (1) Process understanding and assimilation / modeling capabilities of atmospheric convection, mesoscale organization, and atmosphere and ocean boundary layers, (2) Global initial conditions relevant to these quantities/processes. Observations needed for boundary layer, surface conditions, and convection are described in W-1, W-3, and W-4, respectively.	**Most Important**	Vertical temperature profile	Boundary layer through middle atmosphere; threshold Horizontal resolution 5 km, objective Horizontal resolution 3 km, both at 1 km Vertical resolution; threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min; measured with 1 K rms	Polar/geo IR and microwave sounders PLUS GNSS-RO
			Vertical water vapor profile	Boundary layer through middle atmosphere; threshold Horizontal resolution 5 km, objective Horizontal resolution 3 km, both at 1 km Vertical resolution; threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min; measured with 10% LTH rms and 20% UTH rms	Polar/geo IR and microwave sounders PLUS GNSS-RO
			Vertical profiles of horizontal vector winds	Boundary layer through middle atmosphere; threshold Horizontal resolution 5 km, objective Horizontal resolution 3 km, both at 1 km Vertical resolution; threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min; measured at 3 m/s rms	Doppler wind lidar AMVs from IR, WV, and visible imagers and hyperspectral sounders
			Vertical profile of atmospheric O_3, aerosols, and dust for subseasonal	From surface through middle atmosphere mid-troposphere for aerosols and dust; through stratosphere for ozone.	Lidar, stereo visible, UV backscatter, MW limb sounding
			Vertical distributions of clouds and precipitation particles	From surface through lower stratosphere; Vertical resolution 1 km/10 km; ice water path to within 25%, LWP to within 25%	MW for LWP, submillimeter with radar for IWP; GNSS-RO (L-band) dual-pol - LHCP is new

WEATHER AND AIR QUALITY PANEL

SCIENCE			MEASUREMENT		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches Method**
			Precipitation: total amount and rate	Horizontal resolution 10 km, 20%	Passive microwave (e.g., GPM), radar; complemented by rain gauges and radar over land
			Surface pressure	To within 1 mb	
			Vertical profiles of latent heating		GPROF from TRMM, also from CloudSat, GPM
			Sea-ice coverage	5 km resolution; 80% coverage daily; uncertainty 10%; 10 km horizontal	Doppler scatterometer or scatterometer, SAR, high-resolution imager, [ice stations]
			Sea-surface temperature	0.2 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3 to 5 km resolution.	IR radiometer, microwave radiometer, [complemented by in situ buoys and gliders]
			Land-surface temperature	0.6 K random uncertainty in 25 × 25 km area, 80% daily coverage, 3-5 km resolution, with 1 km resolution desired.	IR radiometer (e.g., MODIS, VIIRS, AIRS, CrIS), complemented by modeling
			Snow coverage (for exposed land and ice)	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 1 to 10 km resolution; random errors of two times the resolution.	Visible imager (coverage), passive microwave, radar, and lidar (for snow depth/water equivalent)
			Soil moisture (surface to root zone)	Random errors of 10% in fraction of saturation, while 1 km resolution is desired, 25 km is useful.	Multichannel radiometer, scatterometer (e.g., SMOS, SMAP). *NOTES: C-band scatterometry has worked well in Europe, whereas in the US radiometry is more common. Both seem to work.*
			Ocean mixed layer depth (heat content), sea-surface height, and bottom pressure	Global refresh 10 days; Horizontal 25 km; 0.5 W/m^2/yr per decade.	Altimeter (e.g., Jason, SARAL), gravimeter (e.g., GRACE), [in situ profiles]
			Sea-ice thickness	50 cm; 10 km; 24 hr.	Altimeter (e.g., Jason, ICESat-2)
			Snow water equivalent	Horizon resolution of 20 km, once per day, 10%, Desire 4 km resolution, on a 3 to 5 day scale.	Passive microwave, radar, and SAR
***QUESTION W-3.* Surface Spatial Variations Impacts on Mass and Energy Transfers.** How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, cryosphere) and thereby influence weather and air quality?	**W-3a.** Determine how spatial variability in surface characteristics modifies regional cycles of energy, water and momentum (stress) to an accuracy of 10 W/m^2 in the enthalpy flux, and 0.1 N/m^2 in stress, and observe total precipitation to an average accuracy of 15% over oceans and/or 25% over land and ice surfaces averaged over a 100 × 100 km region and 2- to 3-day time period.	**Very Important**	Ocean surface vector wind or surface wind stress	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 5 to 10 km resolution; 0.02 N/m^2 for 100 km scales and 1 to 2 day averages (this is analogous to vector component wind random errors <1 m/s for the proposed sampling).	Scatterometer OR polarimetric radiometer. *NOTES: SAR could provide wind vectors but directional accuracy not sufficient to calculate curl.*
			Ocean surface vector current	An average of 1-2 samples (overpasses) per day per 100 to 200 km region for a high inclination orbit; 5 to 10 km resolution; Random errors $\leq$0.02 m/s for 100 km scales and 1 to 2 day averages (this is analogous to current random errors <0.5 m/s for the proposed sampling); Coincidence with wind observations.	Doppler scatterometer, HF radar (near coastal only, roughly 100 km from shore). *NOTES: Wide swath altimetry will be complementary but is not an alternative. SAR could provide one vector component, but the accuracy and sampling are questionable. Accurate surface currents (true surface, not subsurface) are new and unique.*
			Subsurface current	Already exceeded by the global drifting buoy network: 1,250 drifting buoys with global ocean coverage and hourly locations.	[Surface drifting buoys drogued to 15 m depth, gliders]

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SCIENCE			MEASUREMENT		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches Method**
			Sea-ice motion	3 km per day; 25 km horizontal, 24 hr.	Doppler scatterometer or scatterometer, SAR, high-resolution imager, (ice stations). *NOTES: Synergetic with observation of sea-ice age and extent, soil moisture, vegetation, snow, ocean mixed layer and surface currents.*
			Sea-ice coverage	5 km resolution; 80% coverage daily; uncertainty 10%; 10 km horizontal	Doppler scatterometer or scatterometer, SAR, high-resolution imager, [ice stations]
			Sea-surface temperature	0.2 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3 to 5 km resolution.	IR radiometer, microwave radiometer, [complemented by in situ buoys and gliders]
			Sea-ice surface temperature	0.6 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3-5 km resolution.	IR radiometer (e.g., MODIS, VIIRS, AIRS, CrIS), complemented by modeling
			Land-surface temperature	0.6 K random uncertainty in 25 × 25 km area, 80% daily coverage, 3-5 km resolution, with 1 km resolution desired.	IR radiometer (e.g., MODIS, VIIRS, AIRS, CrIS), complemented by modeling
			Snow coverage (for exposed land and ice)	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 1 to 10 km resolution; random errors of boundaries of two times the resolution.	Visible imager (coverage), passive microwave, radar, and lidar (for snow depth/water equivalent)
			Soil moisture (surface to root zone)	Random errors of 10% in fraction of saturation while 1 km is desired, 25 km is useful.	Multichannel radiometer, scatterometer (e.g., SMOS, SMAP). *NOTES: C-band scatterometry has worked well in Europe, whereas in the US radiometry is more common. Both seem to work.*
			Upper canopy moisture content	Random errors of 10% in fraction of saturation.	Multichannel radiometer, high frequency and high inclination angle scatterometer
			Significant wave height	5cm random error for a 25 km × 25 km area in one overpass.	Altimeter (for swell, wind wave compoent is well-estimated from surface winds), complemented by wave buoys
			Columnar water vapor (all sky)	An average of 1-2 samples (overpasses) per day per 50 km region; 5 to 10 km resolution; clear sky RMS errors within 3 mm; NWP needs higher revisit (1-6 hr).	Polar/geo IR and microwave sounders PLUS GNSS-RO
			Cloud fraction	An average of 1-2 samples (overpasses) per day per 50 km region, 5 to 10 km resolution, random errors <1 K in brightness temperature	Polar/geo IR
			Ocean mixed layer depth (heat content), sea-surface height, and bottom pressure	Global refresh 10 days; Horizontal 7 km; 0.5 $W/m^2/yr$ per decade.	Altimeter (e.g., JASON, SARAL), gravimeter (e.g., GRACE), [in situ profiles]
			Boundary-layer height (via air temperature profile)	An average of 1-2 samples (overpasses) per day per 50 km region; 5 to 10 km resolution; random errors 10 m in boundary-layer height.	Lidar (e.g., CALIPSO)
			Land surface emissivity	Horizon resolution of 20 km; once per day; 20%. Desire 0.1 km, resolve diurnal cycle 10%	Multiangle multichannel radiometer

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			Ice surface emissivity	Horizon resolution of 20 km; once per day; 0.02.	Multichannel radiometer
			Sea-surface height	10 cm random variability; six hourly; 10 km resolution.	Wide-swath altimeter, supported by microwave water vapor radiometer
			Sea-surface salinity	An average of 1-2 samples (overpasses) per 10 days per 100 to 200 km region; 50 km resolution; random erros of 0.2 psu in monthly average on a 100 × 100 km scale.	L-band radiometer, with co-aligned L-band scatterometer for roughness correction (e.g., SMAP, Aquarius, SMOS)
			Sea-ice thickness	50 cm; 10 km; 24 hr.	Altimeter (e.g., JSON, ICESat-2)
			Snow water equivalent	Horizon resolution of 20 km; once per day; 20%. Desire 4 km resolution, on a 3-5 day scale.	Passive microwave, radar, and SAR
			Snow albedo and emissivity	Horizon resolution of 20 km; once per day; 0.01; 5 km resolution is desired.	Multichannel radiometer, microwave and IR/Vis
			2D surface precipitation	Ideally half hourly, but any additional sampling would be very valuable	Dual-frequencey radiometry, radar (e.g., GPM), [rain gauges and radar over land]
			2D ocean surface color	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 5 to 10 km resolution; random errors of 10 per meter.	Radiometry (e.g., PACE), optical imager (e.g., MODIS), OLCI, SLGI)
			Vegetation characteristics	Land cover type, leaf-area index, vegatation fraction, canopy height	IR and visible radiometry, MODIS, VIIRS, imaging lidar (GEDI and ICESat-2)
			Near surface air temperature and humidity	Horizon resolution of 20 km; temporal resolution of 3 hr; 0.3 K.	Microwave sounder (ocean), possibly hyperspectral IR for clear skies
***QUESTION W-4.* Convective Storm Formulation Process.** Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?	**W-4a.** Measure the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm/hour to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.	**Most Important**	Vertical velocity	Global coverage; sample area 200 × 200 km; 5 year mission; Horizontal resolution 2 km; vertical resolution 200 m; temporal resolution 1 min over a 20-30 min period; accuracy 1 m/s.	Doppler radar
			Precipitation rate	Global coverage; sample area 200 × 200 km; 5 year mission; Horizontal resolution 1 km; temporal resolution 1-5 min; accuracy 1 mm/hr.	Microwave, radar (e.g., GPM), [ground-based gauges and radar]
			3D condensate	Accuracy 0.1 g/kg	Submillimeter multiple frequencies 180-900 GHz
			Vertical profiles of horizontal winds	Accuracy 1 m/s	Doppler wind lidar AMVs from IR/hyperspectral for wind estimation
			3D water vapor	Vertical resolution 1 km; spatial resolution 500 m; temporal resolution 15 min; accuracy 0.5 g/kg.	IR, hyperspectral, [in situ: rawinsonde, aircraft]
***QUESTION W-5.* Air Pollution Processes and Distribution.** What processes determine the spatio-temporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?	**W-5a.** Improve the understanding of the processes that determine air pollution distributions and aid estimation of global air pollution impacts on human health and ecosystems by reducing uncertainty to <10% of vertically-resolved tropospheric fields (including surface concentrations) of speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2).	**Most Important**	PM concentration and properties, including speciation	PM: Aerosol Optical Depth to infer PM from 0-2 km layer; Six observations during daylight hours to get diurnal distribution. 5 × 5 km^2 horizontal resolution. Spectral properties to infer PM speciation.	Combine advanced space-based observations, aircraft and ground-based observations with chemical transport modeling to infer surface levels. Geosynchronous orbit (GEO) to get temporal evolution and high horizontal resolution, in addition to LEO to get global coverage and allow for tracking long-range transport of pollution. A satellite at Lagrange point-1 may provide daylight-side coverage potentially hourly. PM: radiometric and polarimetric

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Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches Method**
					instrument (e.g., NASA EV MAIA, MISR)
			Ozone (O_3) concentration	O_3: Chappuis and other UV bands to infer O_3 from 0-2 km layer, and supported by modeling to infer surface level. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible spectrometer at geo (e.g., TEMPO); commercial aircraft vertical observations during takeoff/landing
			NO_2 (nitrogen dioxide) concentration	NO_2: Lower tropospheric vertical distribution to infer NO_2 from 0-2 km layer. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible (e.g., Aura OMI, ESA TROPOMI, TEMPO); commercial aircraft vertical observations during takeoff/landing
***QUESTION W-6.* Air Pollution Processes and Trends.** What processes determine the long-term variations and trends in air pollution and their subsequent long-term recurring and cumulative impacts on human health, agriculture, and ecosystems?	**W-6a.** Characterize long-term trends and variations in global, vertically resolved speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2) trends (within 20%/yr), which are necessary for the determination of controlling processes and estimation of health effects and impacts on agriculture and ecosystems.	**Important**	PM concentration and properties, including speciation	PM: Aerosol Optical Depth to infer PM from 0-2 km layer; Six observations during daylight hours to get diurnal distribution. 5 × 5 km^2 horizontal resolution. Spectral properties to infer PM speciation.	Combine advanced space-based observations, aircraft and ground-based observations with chemical transport modeling to infer surface levels. Geosynchronous orbit (GEO) to get temporal evolution and high horizontal resolution, in addition to LEO to get global coverage and allow for tracking long-range transport of pollution. A satellite at Lagrange point 1 may provide daylight-side coverage potentially hourly. PM: radiometric and polarimetric instrument (e.g., NASA EV MAIA, MISR)
			O_3 (ozone) concentration	O_3: Chappuis and other UV bands to infer O_3 from 0-2 km layer, and supported by modeling to infer surface level. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible spectrometer at geo (e.g., TEMPO); commercial aircraft vertical observations during takeoff/landing
			NO_2 (nitrogen dioxide) concentration	NO_2: Lower tropospheric vertical distribution to infer NO_2 from 0-2 km layer. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible (e.g., Aura OMI, ESA TROPOMI, TEMPO); commercial aircraft vertical observations during takeoff/landing
***QUESTION W-7.* Tropospheric Ozone Processes and Trends.** What processes determine observed tropospheric ozone (O_3) variations and trends and what are the concomitant impacts of these changes on atmospheric composition/chemistry and climate?	**W-7a.** Characterize tropospheric O_3 variations, including stratospheric-tropospheric exchange of O_3 and impacts on surface air quality and background levels.	**Important**	O_3 (ozone) concentration	O_3: Vertical distribution within the troposphere and lower stratosphere through a combination of ozonesondes (0.5 km vertical resolution, weekly sampling, to 70 hPa) and satellites (e.g., 0.5 km in vertical resolution in upper troposphere, lower stratosphere; 5.5 km^2 column observation with near surface (0-2 km) sensitivity).	Filter radiometer (e.g., Aura HIRDLS) for upper troposphere/lower stratosphere O_3 in conjunction with an ozonesonde network and commercial aircraft observations during takeoff/landing.

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Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches Method**
***QUESTION W-8.* Methane Source Trends and Processes.** What processes determine observed atmospheric methane (CH_4) variations and trends and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate?	**W-8a.** Reduce uncertainty in tropospheric CH_4 concentrations and in CH_4 emissions, including uncertainties in the factors that affect natural fluxes.	**Important**	CH_4 (methane) concentration	CH_4 column (LEO): 7 × 7 km^2 horizontal resolution; daily overpass; precision = 0.6% (upcoming TROPOMI specifications – full physics method). CH_4 column (GEO): 4 × 4 km^2 horizontal resolution; hourly observations; precision = 1.0% (GEO-CAPE specifications) Both TROPOMI and GEO-CAPE may be able to resolve large point sources on daily scales.	Passive instruments give global coverage of columns (e.g., SCIAMACHY), but stymied by clouds and low light conditions. Emissions estimated from a model using satellite-observed methane and proxies (e.g., inundation depth) for emissions.
				Active: pencil pixel size; along track coverage, precision = 1.0% (specifications for upcoming MERLIN)	Active lidar instruments give data in regions that passive instruments cannot, such as night, low light and/or cloudy environments (e.g., monsoons, Arctic).
***QUESTION W-9.* Role of Cloud Microphysical Processes.** What processes determine cloud microphysical properties and their connections to aerosols and precipitation?	**W-9a.** Characterize the microphysical processes and interactions of hydrometeors by measuring the hydrometeor distribution and precip rate to within 5%.	**Important**	3D hydrometeor concentration and drop size distribution	0.5 g/kg	Microwave, IR
			Vertical temperature profile	Horizontal resolution: 3 km; 1 km vertical; refresh; global 90 minutes, CONUS 60 minutes.	Microwave and IR sounders, GNSS-RO
			Vertical water vapor profile	Horizontal resolution: 3 km; 1 km vertical; refresh; global 90 min CONUS 60 minutes.	Microwave and IR sounders, GNSS-RO
			Vertical profiles of horizontal wind vector	Horizontal resolution: 3 km; 1 km vertical; refresh; global 90 minutes and CONUS 60 minutes.	Doppler wind lidar, AMVs from IR, WV and visible imagers and sounders
			Precipitation rate	1 mm/hr accuracy; 2 km horizontal resolution; 1 min temporal refresh over a 20-30 min period.	
			Aerosol concentration	Aerosol optical depth (300 m resolution)	Nadir and multiangle radiometers (MODIS, MISR), lidars (CALYPSO, HRSL), Sun photometers (ground based) for calibration/validation.
***QUESTION W-10.* Clouds and Radiative Forcing.** How do clouds affect the radiative forcing at the surface and contribute to predictability on time scales from minutes to subseasonal?	**W-10a.** Quantify the effects of clouds of all scales on radiative fluxes, including on the boundary layer evolution. Determine the structure, evolution and physical/dynamical properties of clouds on all scales, including small-scale cumulus clouds.	**Important**	High-resolution 2D cloud fraction, helpful to also have estimates of cloud depth, and cloud droplet distribution; Ground-based radiation, water vapor, horizontal and vertical winds, temperature; Hydrometeors, temperature, moisture, winds from the boundary layer through the troposphere and into the UTLS; 3D aerosols, hydrometeors, vertical and horizontal winds, water vapor, temperature, precipitation.	Within 2% for cloud fraction over a 5 × 5 km area; spatial resolution 200 m desirable.	High-resolution visible/IR