TECHNICAL REFERENCE DOCUMENT

IMPROVING WEATHER FORECASTING

1. Introduction

Improving weather information is an international concern. Severe weather events (tornadoes, blizzards, hail, tropical storms such as hurricanes, and extra-tropical storms such northeasters) impact every person and nation on the face of the Earth. These events cause short-lived and long-term hazards, such as flash floods, storm surge and droughts, the latter often leading to wildfire events which further complicate interactions with regional weather, air quality and climate. Each year, tens of thousands of lives are needlessly lost and many billions of dollars in avoidable economic impact result because of the inability to reliably forecast and warn decision makers and the public about impending weather hazards. Furthermore, worldwide socioeconomic sectors (including agriculture, energy distribution, construction, financial, tourism and recreation, public health, ecosystems and biodiversity) are directly affected by severe changes in temperature, precipitation and other general weather conditions. These sectors need improved and extended lead-time weather forecasts to improve productivity, cut costs and/or reduce losses. Scientific research, of El Nino as a case in point, is providing the foundation for more accurate weather forecasts and warnings. Achievable improvements in Earth observations, however, are needed to understand underlying physical phenomena and reduce model uncertainties.

The societal benefits of weather observation are many and date back to the early days of civilization, affecting food production and human migration. Weather prediction improvements yield savings in life, property, and infrastructure. Aviation safety, for example, could be improved through better knowledge of the location and quantity of super cooled liquid water and volcanic ash emissions. Transportation costs could be reduced through better knowledge of the sea surface wind and sea ice for transoceanic ship routing. More accurate weather predictions could result in significant savings for the energy industry, such as better matching of supply to projected demand. Better forecasts are important in planning disaster assessment and emergency response. The commodities market could also benefit from improved weather forecasts. Improved weather observations, assimilated into numerical weather prediction (NWP) models, would yield quantitative improvements in global and regional forecast capability. Improvements could be expected in areas such as regional forecasting of rain and snow, forecasting of winter storms on the local level, hurricane landfall accuracy, tornado lead-time, and prediction of thunderstorm occurrence. These improvements would yield easily appreciable benefits to the public.

While even perfect forecasts will not prevent all losses due to weather and floods, further forecast and warning improvements will lessen these losses. For example, the annual cost of electricity could decrease by at least $1 billion per year, if the accuracy of temperature forecasts improved by

1 degree Fahrenheit [1]. Better preparation, response, and mitigation could reduce the average annual cost of storm-related disasters by approximately 10 percent or $700 million per year [2]. Improved flash and river flood forecasts will save lives and an estimated $240 million per year in flood losses [3]. Worldwide agriculture benefits from better El Niño forecasts could exceed $500 million per year [4].

A U.S. Integrated Earth Observation System and Improving Weather Forecasting—A Necessary Synergy

Improving weather forecasting is one of nine preliminary societal benefit areas, which are the focus of the planned U.S. Integrated Earth Observation System. The nine preliminary benefit areas are:

- Improve Weather Forecasting
- Reduce Loss of Life and Property from disasters
- Protect and Monitor Our Ocean Resource
- Understand, Assess, Predict, Mitigate, and Adapt to Climate Variability and Change
- Support Sustainable Agriculture and Forestry, and Combat Land Degradation
- Understand the Effect of Environmental Factors and Human Health and Well-Being
- Develop the Capacity to Make Ecological Forecasts
- Protect and Monitor Water Resources
- Monitor and Manage Energy Resources

These areas are linked and not mutually exclusive, especially in the area of weather forecasting. For example, weather forecasting improvements could likely lead to reducing loss of life and property from disasters, better energy resource management, and better sustained agriculture. The Earth is an integrated system. All the processes that influence conditions on the Earth (whether ecological, biological, climatological, or geological) are linked and impact one another. As illustrated in Figure 1, current weather observing systems (to be discussed in further detail in Section 3) provide environmental data and information necessary for realizing the other specified benefits. However, weather forecasting improvements depend on feedback from those areas. Figure 2 illustrates the types of information and insight the weather community needs to produce more accurate specification and forecasts of environmental phenomena impacting the societal benefit area of interest. For example, better specification of soil properties and crop coverage from agriculture is necessary for better forecasts from numerical prediction models for farmers.

A U.S. Integrated Earth Observation System contributes to improving weather information in three ways. This integrated system provides a timely, comprehensive initial synoptic view (or "Earth" picture), which is crucial to more specific short-range forecasts—more timely and accurate weather information available to decision-makers. This integrated system also provides comprehensive observations necessary to extend the range of useful products—reducing the impact of weather on a larger number of global inhabitants and regions. Furthermore, this integrated system provides an organization and infrastructure allowing U.S. participating agencies to more efficiently address their end-to-end weather information services needs—resulting in greater service for less cost.

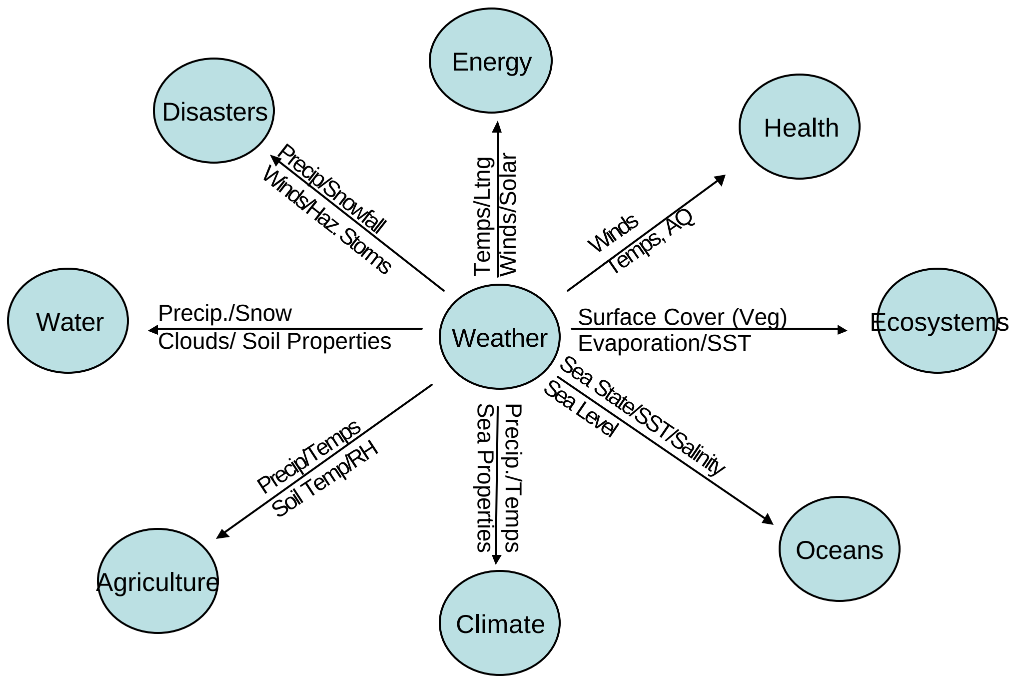


Figure 1: Weather data and information critical to realizing other societal benefits

More specifically, models will exploit improved observations from the U.S. Integrated Earth Observation System to yield weather forecasts of sufficient quality that many disciplines, which are currently structured to cope reactively with weather as it occurs, will transition to operations that proactively anticipate threats and take action days in advance. For example, energy generation decisions made 4-6 days in advance of heat waves and cold snaps based on accurate weather forecasts can save millions of dollars. Accurate forecasts of excessive temperatures and humidities will allow health officials to anticipate and adequately staff for heat-stress-related emergencies. Similarly, accurate weather forecasts will allow: the agriculture sector to take measures to protect crops; ecological monitoring teams to evolve beyond tracking to predicting biological invasions; and disaster teams to minimize the impact of potentially catastrophic environmental events threatening life and property.

In summary, the U.S. Integrated Earth Observation System contributions not only improve weather information, but, in doing so, also produce derivative contributions to the other societal benefit areas, creating an interdisciplinary synergistic approach to addressing societal needs—

thereby improving the utilization of information, its overall quality and reducing development costs.

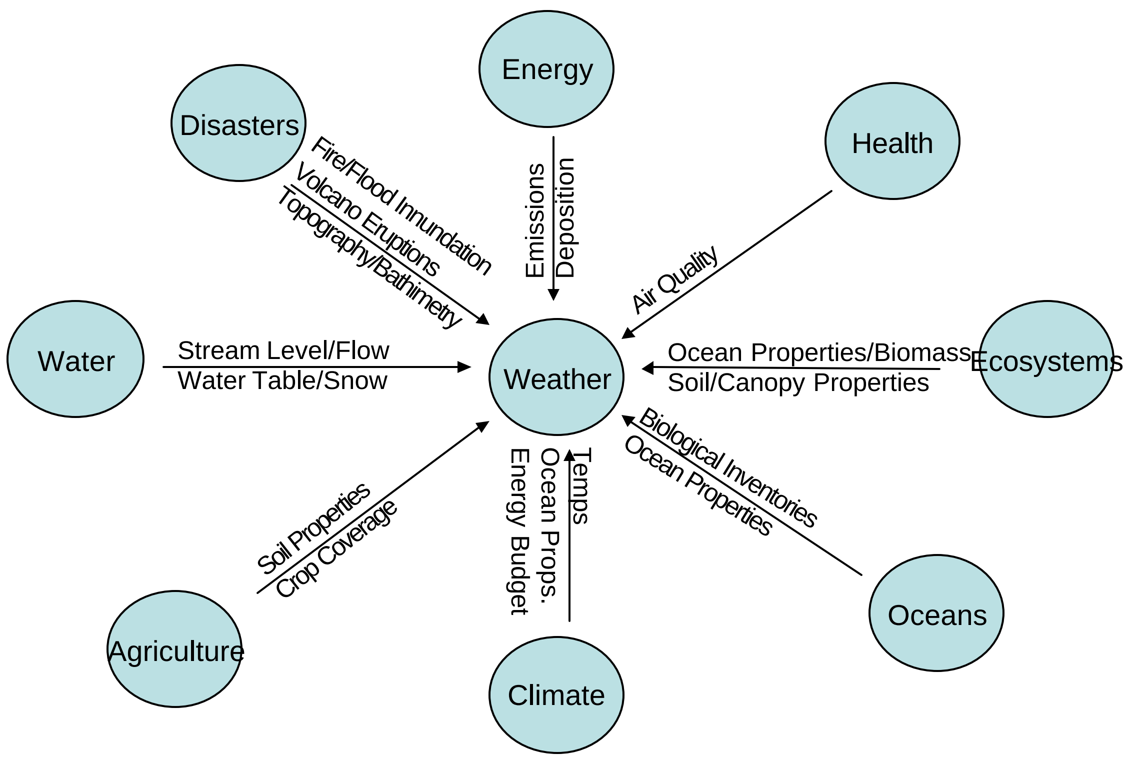


Figure 2: Other societal benefit data necessary to improve weather forecasting capabilities

Weather Forecasting—A Benchmark for U.S. and International Cooperation

Sustained global cooperation on Earth observations is well established in the area of weather, as acknowledged by the ministers from 47 countries attending the Second Earth Observation Summit in Tokyo, Japan on April 25, 2004. The Framework Document, adopted by the ministers at the Summit, recognized the World Meteorological Organization (WMO) World Weather Watch as demonstrating the value of international collaboration in the weather area, but stated that improvements in observation networks are still needed and will yield further success through improved accuracy in weather information and long-term prediction [5]. The U.S. has been an active participant in WMO activities for over 50 years.

Within the U.S., the area of weather is equally well established, with well-defined organizational missions to provide a continuum of weather support. This continuum includes:

- Operations and services, which includes education and training, observing system deployment and operational implementation
- Applied research to solve immediate problems, through forecast technique development, hazard detection algorithms and proof of concept activities
- Basic research to increase the fundamental understanding of the weather through theoretical studies, numerical simulations, and field projects

The operations and services part of the continuum is the domain of individual agencies. The basic and applied research parts of the continuum are the domain of the U.S. Weather Research Program (USWRP), an interagency partnership that provides the essential focal point and organizational driver for moving ideas and technology from the research arena to operational implementation in order to achieve the goal of greatly improved weather prediction [6].

Over the past 40 years, provision of weather services within the U.S. has evolved from an almost exclusively governmental function to one carried out by the public sector (a combination of federal, state, and local government agencies), the private sector and academia. Partnerships exist at all levels (described further in Section 6) to support meeting the weather needs of an increasingly diverse user community [7].

On the federal level, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (also known as the Office of the Federal Coordinator for Meteorology (OFCM)) ensures the effective use of federal meteorological resources by leading the systematic coordination of operational weather requirements and services, and supporting research, among the federal agencies (http://www.ofcm.gov). Fifteen federal agencies are currently engaged in meteorological activities and participate in the OFCM's coordination and cooperation infrastructure. Each year, OFCM prepares *The Federal Plan for Meteorological Services and Supporting Research* for the next fiscal year. This Congressionally mandated plan is a one-of-a-kind document, which articulates the meteorological services, provided and supporting research conducted by federal agencies. The Fiscal Year 2004 plan can be found at http://www.ofcm.gov/fp-fy04/fedplan.htm.

In the operational domain, the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) is the primary source of weather, water, and climate data, forecasts and warnings for the U.S., its territories, adjacent waters, and ocean areas. The NWS operates the most advanced weather and flood warning and forecast system in the world, helping to protect lives and property and enhance the national economy. NOAA is dedicated to enhancing economic security and national safety through the research and prediction of weather and climate-related events and providing environmental stewardship of the nation's coastal and marine resources.

NWS, through its National Centers for Environmental Prediction (NCEP), delivers national and global weather, water, climate and space weather analyses, forecasts, warnings and guidance to its Partners and External User Communities. These products and services are based on a service-science legacy and respond to user needs to protect life and property, enhance the nation's economy and support the nation's growing need for environmental information. NCEP provides tailored services through the following 9 centers:

- Aviation Weather Center—provides warnings and forecasts of hazardous flight conditions at all levels within the domestic and international airspace.
- Climate Prediction Center— assesses and forecasts the impacts of short-term climate variability, emphasizing enhanced risks of weather-related extreme events, for use in mitigating losses and maximizing economic gains.
- Environmental Modeling Center—improves numerical weather, marine and climate predictions at the National Centers for Environmental Prediction through a broad program of research in data assimilation and modeling.
- Hydrometeorological Prediction Center— provides analysis, forecast, and guidance products and services in support of the daily public forecasting activities of the National Weather Service and its customers, and tailored weather support to other government agencies in emergency and special situations. Focuses on heavy precipitation forecasting, winter weather forecasting, medium-range forecasting, real-time numerical model diagnostics and interpretation, and surface analyses.
- Ocean Prediction Center— continually monitors and analyzes maritime data, originates and issues marine warnings and forecasts, and provides guidance of marine atmospheric variables for purposes of protection of life and property, safety at sea, and enhancement of economic opportunity. These products fulfill U.S. responsibilities with the World Meteorological Organization and Safety of Life at Sea Convention (SOLAS) [International Convention for the Safety of Life at Sea, 1960 and 1974].
- Space Environment Center—continually monitors and forecasts Earth's space environment; provides accurate, reliable and useful solar-terrestrial information; conducts and leads research and development programs to understand the space environment and to improve services.
- Storm Prediction Center—provides short-term forecasts of hazardous weather to the public and the NWS local field offices.
- Tropical Prediction Center—issues analyses, forecasts, watches, and warnings of hazardous tropical weather.
- NCEP Central Operations—sustains and executes the operational suite of the numerical analyses and forecast models and prepares NCEP products for dissemination.

Through the operation of the nine centers described above, the NWS is the most well-known government provider of weather services. However, several other federal agencies also provide weather-related services (operational and/or research):

- Department of Agriculture (USDA)--operating specialized weather observation networks and conducting active supporting research to ensure an abundance of high-quality agricultural commodities while minimizing the adverse effects of agriculture on the environment
- Department of the Interior (DOI)--supporting the Bureau of Land Management's remote automatic weather station program
- Environmental Protection Agency (EPA)--providing user-appropriate and scientifically credible air-quality meteorological programs to support regulatory applications
- National Aeronautics and Space Administration (NASA)--aviation weather research, Earth Observing System and Earth Probe instruments
- Nuclear Regulatory Commission (NRC)--obtaining and analyzing meteorological data and information related to siting new nuclear power plants and safe operation of nuclear facilities, the protection of public health and safety and protection of the environment
- Department of Transportation (DOT)--through the Federal Aviation Administration (FAA) Weather and Radar Processor (WARP), disseminating aviation weather information throughout the National Airspace System (NAS) and operating of WSR-88D Doppler weather radar, Automated Surface Observing System (ASOS), and automated weather information systems
- Department of Defense (DoD)--acquiring the National Polar-orbiting Operational Environmental Satellite System (NPOESS), operating WSR-88D, ASOS and automated weather information systems, and supporting DoD operational weather requirements
- Department of Energy (DOE)—providing meteorological services for national defense projects and homeland security at DOE and National Nuclear Security Administration (NNSA) sites; operating the National Atmospheric Release Advisory Center (NARAC); and conducting research and development regarding climate change, radiation transfer mechanisms and cloud studies, atmospheric chemistry and studies of atmospheric boundary layer processes
- Department of Homeland Security (DHS)--providing atmospheric transport and diffusion modeling and plume forecasts

Illustrating the effective national cooperation in improving weather forecasting services, these agencies, working together through OFCM, have accomplished the following over the past two years:

- Developed a Homeland Security Environmental Support Plan
- Published the Weather Information for Surface Transportation National Needs Assessment Report
- Implemented of a more rigorous, scientific-based Wind Chill Temperature Index
- Published the Aviation Weather Program Mid-Course Assessment, a periodic review of progress in improving aviation weather safety
- Completed requirements definition for a new national lightning data contract
- Investigated the applicability of phased array radar technology for use in upgrading current weather radar capabilities
- Collaborated with the National Academy of Sciences/National Research Council to examine research opportunities and required services to improve weather forecasting for the Nation's roadways
- Broadened agency participation with USWRP to accelerate forecast improvements of high impact weather and to facilitate full use of advanced weather information

2. User Requirements

Benefiting from the strong international and national cooperation in improving weather forecasting mentioned above, the specification and prioritization of weather observation is well established. Internationally, the World Meteorological Organization (WMO) has a long history of defining its weather observational data requirements. Guided by its Long-term Planning Process, the WMO presently follows a process that results in a hierarchical set of requirements. The Sixth Long-term Plan is the current plan and spans the time frame 2004 to 2011. The current procedure for setting, reviewing and updating weather observational data requirements by the various WMO Technical Commissions is called the Rolling Review of Requirements (RRR). The RRR procedure consists of four stages: a review of users' requirements for observations, within areas of applications covered by WMO programs; a review of the observing capabilities of existing and planned satellite and *in situ* systems; a critical review of the extent to which the capabilities meet the requirements; and a resulting statement of guidance. Requirements for observations are stated quantitatively in terms of a set of relevant parameters, of which the most important are horizontal and vertical resolution, frequency (observing cycle), timeliness (delay of availability), and accuracy (http://www.wmo.ch).

Working with input from the RRR process, the WMO Expert Team on Observational Data Requirements and Redesign of the Global Observing System (GOS) has developed a vision for the GOS of 2015, which includes an observation component (with both remote sensing and *in situ* systems), and a data management component. This vision document provides a prioritized list of critical atmospheric parameters that are not adequately measured by current or planned observing systems. Those parameters in order of priority are:

- Wind profiles at all levels
- Temperature profiles of adequate vertical resolution in cloudy areas
- Precipitation
- Soil moisture
- Surface pressure
- Snow equivalent water content.

Additionally, the document provides a prioritized list of recommendations, in two categories, to facilitate development of this future system. Those categories are: satellite systems and *in situ* systems. Table 1 summarizes the priorities, the details of which are included in the WMO GOS 2015 vision document [8].

Priority	**Satellite**	***In Situ***
1	Calibration	Data Distribution and Coding
2	GEO Imager	AMDAR Development
3	GEO Sounder	Ground-based GPS
4	GEO Imager/Sounder	Improved Observations--Ocean Areas
5	LEO Data Timeliness	Improved Observations--Tropical Land Areas
6	LEO Temporal Coverage	New Observing Technologies
7	LEO Sea Surface Winds	
8	LEO Altimeter	
9	LEO Earth Radiation	
10	R&D LEO Doppler	
11	R&D Precipitation	
12	R&D Radio Occultation	

Table 1: Prioritized Recommendations for WMO Global Observing System of 2015

The above specific observing priorities were used by an international team developing the "Improving Weather Information, Forecasting and Warning" section of the Implementation Plan for the Global Earth Observation System of Systems (GEOSS). This team recognized that, in addition to the above specific observing priorities, the following general end-to-end weather information services priorities exist:

- Full access to GEOSS information (necessary policies, interoperability standards, dissemination technologies)
- Enhanced data initialization and assimilation capabilities to facilitate full use of the expanded remotely-sensed and *in situ* observations captured through GEOSS

- Necessary Research and Development activities, related to new archive, access and data processing (including numerical modeling) capabilities, to ensure sustained weather information for the long-term
- Sufficient education and training to enable full worldwide use of GEOSS

These international priorities form a basis for U.S. national weather forecasting priorities, as the U.S. is an active participant in the WMO World Weather Watch program.

Within the U.S. several national studies have shown that present and future users will require access to weather data that are more detailed and available in less time. These users will require access to environmental data and information within minutes, hours, or days of the recorded observations, depending on the type of application for the data [9, 10 and 11]. New and improved weather products are leading to new users, such as the "weather derivatives" industry [12]. Weather derivatives are financial instruments that allow energy and other companies sensitive to weather variability to spread out the risk associated with these uncertainties by purchasing insurance against such risks. A multibillion-dollar industry that provides this protection against weather risks has emerged—an industry that is very sensitive to accurate weather forecasts and accurate historical climate data [13].

Based upon an active, continuous dialogue with mission partners, NWS has determined users (including NWS field offices, other governmental agencies, the media, the private sector, academic institutions, the international community, and the general public) have the following priorities:

- Increased coverage and resolution of observations—to improve the accuracy of depictions of critical phenomena and processes enabling more accurate and extended lead-time warnings and forecasts.
- Observations of environmental elements not presently observed—to improve existing and enable the creation of new warning and forecast products.
- Improved timeliness, data quality, and long-term continuity of observations—to reduce analysis and model initialization error; increase forecast accuracy; extend warning lead times; and maintain the climate record.
- Integrated multi-purpose observing systems and networks which allow rapid dissemination of weather information—to cost-effectively meet multi-purpose observational requirements and to provide more timely data access.

Table 2 lists the NWS-derived listing of common weather observations needed to perform the specified weather forecasting and warning mission.

	Weather Missions				
Geo-Physical Parameters	**Flash Flood Warnings**	**Tropical Storm Warnings**	**Winter Storm Warnings**	**Severe Thunderstorm Warnings (Wind, Hail, Tornados)**	**Transport Safety (ground and air)**
Cloud Properties	X	X	X	X	X
Soil Properties	X		X	X	X
Pressure Surface Height	X	X	X	X	X
Lake/River/Sea Ice Properties	X		X		X
Electro-Static Discharge	X	X	X	X	X
Precipitation Properties	X	X	X	X	X
Atmospheric Moisture	X	X	X	X	X
Other Lake/River/Sea Properties (salinity, flow rate, level, temperature)	X	X	X		
Land Surface Properties	X	X	X	X	X
Atmospheric Temperature	X	X	X	X	X
Atmospheric Winds	X	X	X	X	X
Atmospheric Vertical Motion	X	X	X	X	X
Visibility Properties (e.g. dust, smoke, haze, fog)			X	X	X
Land Surface Snow Properties	X		X		X

Table 2: Observations Required for Successfully Meeting Weather Missions

Another national source of common weather observation requirements is the Integrated Operational Requirements Document for the National Polar-orbiting Operational Environmental Satellite System. This requirements document contains a detailed requirements correlation matrix, as well as a set of key performance parameters (KPPs). The listing of these KPPs, contained in the table below, are validated sets of user prioritized environmental requirements.

System Requirement	Threshold	Objective
ATMOSPHERIC VERTICAL MOISTURE PROFILE (measurement uncertainty)		
Clear, surface to 600mb	Greater of 20% or 0.2g kg^{-1}	10%
Cloudy, surface to 600mb	Greater of 20% or 0.2g kg^{-1}	10%
ATMOSPHERIC VERTICAL TEMPERATURE PROFILE (measurement uncertainty)		
Clear, surface to 300mb	1.6K/1km layer	None
Cloudy, surface to 700mb	2.5K/1km layer	None
GLOBAL SEA SURFACE WINDS		
Measurement Accuracy (Speed)	Greater of 2m s^{-1} or 10 %	Greater of 1m s^{-1} or 10 %
IMAGERY (Refresh for visible and IR bands)	At any location: a) the avg. revisit time will be 4 hrs or less and the max revisit time will be 6 hrs or less b) at least 75% of the revisit times will be 4 hrs or less	1 Hour
SEA SURFACE TEMPERATURE		
Horizontal Cell Size – Nadir, clear	1 km	0.25km
Measurement uncertainty – clear	0.5 deg C	0.1 deg C
SOIL MOISTURE		
Sensing Depth	Surface (skin layer: -0.1cm)	Surface to –80cm
DATA ACCESS	Capable of selectively denying all U.S. environmental sensor data (except ARGOS and SARSAT7)	None
INTEROPERABILITY	100% of top-level IERs designated as critical	100% of top level IERs

Table 3: Key Performance Parameters for NPOESS

3. Existing Capabilities and Commonalities

The U.S. uses both remote sensing and *in situ* observation systems to collect required weather observations. Earth observation satellites provide an inherent wide area observation capability, non-intrusive observations, uniformity, rapid measurements and continuity. *In situ* observation systems provide measurements unobtainable from space, measurements complementary to those from space and validation of satellite measurements [14]. Weather information providers need observations from both types of systems to provide required weather forecasts. Major observational infrastructure investments by NOAA, NASA, FAA, and DOD provided the bulk of the currently deployed U.S. weather observing capabilities. The U.S. has an impressive space-, surface- and air-based weather observation infrastructure. Below are brief descriptions (including internet URL) of those major U.S. surface- and air-based weather observing systems and weather-related satellites deployed today. Following the brief descriptions, Table 4 depicts the current U.S. weather-related satellites deployed for both research and operational use.

Deployed Non-Satellite Systems

Ameriflux Network The Ameriflux network: provides an infrastructure for guiding, collecting, synthesizing, and disseminating long-term measurements of CO2, water, and energy exchange from a variety of ecosystems; collects critical new information to help define the current global CO2 budget; enables improved predictions of future concentrations of atmospheric CO2; and enhances understanding of carbon fluxes, Net Ecosystem Production (NEP), and carbon sequestration in the terrestrial biosphere (http://public.ornl.gov/ameriflux/Participants/Sites/Map/index.cfm).

Automated Meteorological Reports from Aircraft Automated meteorological reports from aircraft are generically called AMDAR (Aircraft Meteorological Data Relay) reports. In the United States, however, these data are generally referred to as ACARS data. (ACARS stands for Aircraft Communication Addressing and Reporting System, a communication system operated for the airlines by Aeronautical Radio Inc. [ARINC] that reports a number of aircraft parameters such as passenger loading, and dispatch information along with weather information. We use the term ACARS to refer to only the weather information from U. S. carriers.) The U. S. data are also sometimes referred to as MDCRS (Meteorological Data Collection and Reporting System). MDCRS is a database containing ACARS data and a distribution system that feeds the data from ARINC, where the database resides, to NCEP, where the data are used in NCEP's operational models and placed on the GTS (Global Telecommunications System) for distribution to government NWP centers worldwide (http://acweb.fsl.noaa.gov).

Automated Surface Observing System (ASOS) NWS, FAA and DoD operate this network of 967 stations located throughout the U.S. The data generally available from ASOS include hourly observations of air temperature, dew point, wind speed and direction, cloud cover, visibility, present weather, and precipitation (see http://205.156.54.206/asos).

Automated Weather Observing System (AWOS) AWOS is a suite of sensors, which measures, collects and broadcasts weather data to help meteorologists, pilots and flight dispatchers prepare and monitor weather forecasts, plan flight routes, and provide necessary information for correct takeoffs and landings. The FAA and various state agencies operate this network of over 600 stations located throughout the U.S. These stations typically provide 20-minute observations of air temperature, dew point, wind speed and direction, cloud cover, visibility, altimeter setting, present weather and precipitation (http://www.faa.gov/asos/).

Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) BAMEX was a study using highly mobile platforms to examine the life cycles of mesoscale convective systems. The study combined two related programs investigating bow echoes (principally those which produce damaging surface winds and last at least 4 hours) and larger convective systems, which produce long-lived mesoscale convective vortices (MCVs). The main objectives of BAMEX were to understand and improve prediction of the mesoscale and cell-scale processes that produce severe winds (http://www.ofps.ucar.edu/bamex/dm/archive/data_list.html).

Citizen Weather Observer Program (CWOP) CWOP is comprised of weather stations operated by the general public (of which almost 700 stations are in the U.S.) and reported by amateur radio operators around the world. The NOAA Forecast Systems Laboratory collects these observations (http://www.wxqa.com/).

Cooperative Agency Profiler (CAP) Network NOAA FSL collects data from approximately 80 CAP sites around the world, providing vertical profiles of horizontal winds within the atmospheric boundary layer (http://www.profiler.noaa.gov/jsp/aboutCap.jsp).

Cooperative Observer Program (COOP) NWS oversees this network with almost 10,000 participating cooperative observers located throughout the U.S. This network provides daily observations (7am local time) of maximum and minimum air temperature, precipitation, snowfall, and snow depth (http://www.nws.noaa.gov/om/coop/index.htm). The data are archived at the National Climatic Data Center (NCDC).

Integrated Surface Irradiance Study Network (ISIS) ISIS, a network of 9 sites operated by NOAA's Air Resources Laboratory, provides 3-minute observations of downwelling global solar, direct solar, downwelling diffuse and global UVB radiation (http://www.srrb.noaa.gov).

International H2O Project (IHOP 2002) IHOP 2002 was a field project designed to obtain more accurate and reliable measurements of moisture in the air. The project had four main research components: quantitative precipitation forecasting, convection initiation, atmospheric boundary layer interactions, and instrumentation. Although the project is complete, the following URL points to the rich network of national, regional, state and local meteorological networks used during the field project (http://www.joss.ucar.edu/ihop/dm/insitu/sfcmet.html).

Long Term Ecological Research (LTER) Network LTER, a collaborative effort established by the National Science Foundation, involves more than 1800 scientists and students investigating ecological processes over long temporal and broad spatial scales. This network of 24 sites, including at least one automated weather station at each site, promotes synthesis and comparative research across sites and ecosystems and among other related national and international research programs (http://lternet.edu).

NCEP Hourly Precipitation Data NCEP routinely develops a national multi-sensor hourly precipitation analysis (Stage II) data set from hourly radar precipitation estimates and hourly gauge reports from approximately 4000 gauges across the U.S. collected by NOAA River Forecast Centers (http://wwwt.emc.ncep.noaa.gov/mmb/ylin/pcpanl).

NOAA Profiler Network (NPN) NOAA Forecast Systems Laboratory operates this network of 35 unmanned Doppler Radar sites located in 18 central U.S. states and Alaska, providing hourly vertical wind profile data (http://www.profiler.noaa.gov/jsp).

Remote Automated Weather Station (RAWS) Network This interagency network, overseen by the U.S. Forest Service, consists of 726 stations located throughout the U.S., but heavily concentrated in the forested areas of the western mountains. The network provides hourly values of air temperature, dew point, wind speed and direction, precipitation, fuel temperature and fuel moisture (http://www.fs.fed.us/raws).

Soil Climate Analysis Network (SCAN) SCAN, operated by USDA, provides hourly observations of air temperature, relative humidity, wind speed and direction, solar radiation, precipitation, barometric pressure, snow water content, snow depth, soil temperature, and soil moisture collected at 80 stations across the U.S. (primarily agricultural regions (http://www.wcc.nrcs.usda.gov).

Surface Radiation Budget Network (SURFRAD) SURFRAD supports climate research with accurate, continuous, long-term measurements of the surface radiation budget over the United States. Seven SURFRAD stations, operated by NOAA's Air Resources Laboratory, primarily measure upwelling and downwelling, solar and infrared radiation; ancillary observations include direct and diffuse solar, photosynthetically active radiation, UVB, spectral solar, and meteorological parameters (http://www.srrb.noaa.gov/surfrad).

Upper-Air Observations Program NWS manages the operation of 92 Radiosonde stations in North America and the Pacific Islands and supports the operation of 10 stations in the Caribbean. Radiosondes provide upper-air data that are essential for weather forecasts and research (http://www.ua.nws.noaa.gov).

Weather Surveillance Radar 1988 Doppler (WSR-88D) Network NWS and DoD operate this network of 143 WSR-88D radars across the contiguous U.S, providing Level II data (reflectivity, mean radial velocity, and spectrum width) for recording at most sites. This Level II data is then processed in order to create a number of meteorological analysis products including velocity azimuth display wind profiles, 1-hour precipitation, severe weather probability, storm tracking information, and tornadic vortex signature information. All Level II and III data are archived at NCDC (http://www.ncdc.noaa.gov/oa/radar/radarresources.html or http://www.roc.noaa.gov).

Deployed Satellite Systems

Aqua Aqua is one of a series of NASA's Earth Science Enterprise space based platforms and a joint project of the U.S., Japan and Brazil. Aqua carries six instruments (MODIS, AMSR-E, AMSU-A, CERES, AIRS and HSB) and collects data on the Earth's water cycle. NASA is working with NOAA and the European Centre for Medium-Range Weather Forecasts to facilitate incorporation of Aqua data in their weather forecasting efforts (http://eos-pm.gsfc.nasa.gov).

Aura Aura is one of a series of NASA's Earth Science Enterprise space based platforms and a joint project of the U.S., United Kingdom and the Netherlands. Aura carries four instruments (OMI, HIRDLS, TES, and MLS) and collects data on the Earth's atmospheric chemistry and dynamics. These data are key for improving air quality forecasts and climate modeling and prediction (http://www.earth.nasa.gov).

Coriolis Coriolis is a test mission for the flight of two DoD payloads: Windsat and Solar Mass Ejection Imager (SMEI). Windsat is a polarimetric microwave radiometer experiment to passively measure ocean surface wind vectors. SMEI will monitor solar activity, with the goal of more accurately predict geomagnetic disturbances to orbiting satellites (http://nkma.ksc.nasa.gov/payload/missions/coriolis).

Challenging Mini-Satellite Payload for Geo-scientific Research and Applications Program (CHAMP) CHAMP is a cooperative project among the U.S. (NASA and AFRL), Germany and France. CHAMP carries six instruments (LRR, OVM, FGM, DIDM, ACC, and GPS receiver) and will perform atmospheric and ionospheric soundings with applications to global climate studies, weather forecasting, disaster research and navigation (http://op.gfz-potsdam.de/champ/).

Defense Meteorological Satellite Program (DMSP) DMSP is a Department of Defense (DoD) program run by the Air Force Space and Missile Systems Center (SMC). The DMSP designs, builds, launches, and maintains satellites monitoring the meteorological, oceanographic, and solar-terrestrial physics environments. Data from DMSP satellites are received and used at operational weather forecasting centers (NOAA and DoD) continuously and archived at NOAA's National Geophysical Data Center (http://www.oso.noaa.gov/dmsp).

Earth Radiation Budget Satellite (ERBS) ERBS is a NASA satellite, which carries two instruments (ERBE and SAGE II) designed to investigate how solar energy is absorbed and re-emitted by the Earth. ERBS observations are used to determine the effects of human activities (such as burning of fossil fuels) and natural occurrences (such as volcanic eruptions) on the Earth's radiation balance (http://asd-www.larc.nasa.gov/erbe/erbs.html).

Geostationary Operational Environmental Satellite (GOES) GOES, built and launched by NASA and operated by NOAA, provides timely global weather information, including advance warning of developing storms. GOES imagery is commonly featured on many TV weather reports across the United States and the world. The GOES Program maintains two satellites operating in conjunction to provide observational coverage of 60% of the Earth. The GOES satellite system has remained an essential cornerstone of weather observations and forecasting for 25 years. The two-satellite GOES system maintains a continuous data stream in support of the National Weather Service requirements. Current weather satellites can transmit visible or infrared imagery, focus on a narrow or wide area, and maneuver in space to obtain maximum coverage. In addition to an imager, GOES 12, the latest in the current GOES-series satellites, contains four other instruments (Solar X-ray imager, Space Environment Monitor, Atmospheric Sounder, and Search and Rescue package) providing data for use in weather forecasts, disaster management, public health and aviation safety (http://www.goes.noaa.gov).

Gravity Recovery and Climate Experiment (GRACE) GRACE, a joint partnership between NASA and Germany, is primarily designed to map variations in the Earth's gravity field. However, GRACE carries six instruments (Star Camera Assembly, GPS Receiver, IPU, LRR, K-Band Ranging Instruments, and SuperSTAR Accelerometers), which will help provide a better profile of the Earth's atmosphere (http://www.csr.utexas.edu/grace/).

Ice, Clouds, and Land Elevation Satellite (ICESat) ICESat, part of NASA's Earth Observing System (EOS), is primarily designed to quantify ice sheet mass balance and understand how changes in Earth's atmosphere and climate affect polar ice masses an global sea level. However, ICESat's two instruments (GLAS and GPS receiver) measure the distribution of clouds and aerosols, land topography, sea ice and vegetation cover (http://icesat.gsfc.nasa.gov).

Polar-orbiting Operational Environmental Satellite (POES) POES, built and launched by NASA and operated by NOAA, provides atmospheric profiles (temperature, moisture and ozone), radiation budget, cloud cover and storm location information for improved weather forecasting. POES, a two-satellite operational complement to GOES, carries eight instruments (AMSU-A, AMSU-B, MHS, SBUV, DCS, AVHRR, HIRS and Search and Rescue package) for use in weather forecasting, disaster management, public health and aviation safety (http://www.oso.noaa.gov/poes).

Quick Scatterometer (QuikSCAT) QuikSCAT is a NASA satellite designed to measure sea-surface wind speed and direction data under all weather and cloud conditions over the Earth's oceans. QuikSCAT's main instrument, SeaWinds, is an active radar scatterometer that covers 90% of the Earth's surface in one day, providing data vital for operational weather forecasting, storm warning and global climate research (http://winds.jpl.nasa.gov/missions/quikscat/).

Solar Radiation and Climate Experiment (SORCE) SORCE is a NASA-sponsored satellite mission that provides state-of-the-art measurements of incoming x-ray, ultraviolet, visible, near-infrared and total solar radiation. SORCE's four instruments (TIM, SIM A&B, SOLSTICE A&B, and XPS) provide measurements critical to studies of the sun, its effect on the Earth system and its influence on humankind (http://lasp.colorado.edu/sorce).

Terra Terra is the flagship of NASA's Earth Science Enterprise (the first EOS platform), providing global data on the state of the atmosphere, land and oceans, as well as their interactions with solar radiation and with one another. Terra's five instruments (CERES, MISR, MODIS, MOPITT, and ASTER) allow simultaneous study of clouds, water vapor, aerosol particles, trace gases, terrestrial and oceanic properties, the interaction among them and their effect on atmospheric radiation and climate (http://terra.nasa.gov).

Tropical Rainfall Measuring Mission (TRMM) TRMM is a NASA satellite devoted to determining rainfall in the tropics and subtropics of the Earth. A joint NASA/Japan mission, TRMM has five instruments (CERES, LIS, TMI, PR, and VIRS) that provide three-dimensional maps of storm structure, rainfall distribution and intensity and lightning location over the tropics (http://trmm.gsfc.nasa.gov).

Upper Atmosphere Research Satellite (UARS) UARS is a NASA satellite, the first dedicated to studying stratospheric processes. UARS' ten instruments (ISAMS, MLS, HALOE, HRDI, WIND II, SOLSTICE, SUSIM, PEM, ACRIM, and CLAES) measure winds and temperatures in the stratosphere, as well as energy input from the sun (http://umpgal.gsfc.nasa.gov/uars-science.html).

The following table lists satellites deployed for both research and operational use:

Mission	Organizations	Associated Countries	Environmental Parameters
Aqua	NASA	Japan, Brazil	Weather & environment
Aura	NASA	UK, Netherlands	Aerosols & volcanic plumes
CHAMP	DLR/DARA/NASA	Germany, France	Atmospheric temperature
Coriolis	NRL/NOAA/NASA		Ocean surface winds
DMSP	DoD/NOAA		Weather & environment
ERBS	NASA		Earth energy balance
GOES	NOAA/NASA		Weather
GRACE	NASA/DLR	Germany	Atmospheric temperature
ICESat	NASA		Clouds and Aerosols
OrbView-1	ORBIMAGE/NASA		Atmospheric temperature & lightning
POES	NOAA/NASA		Weather & environment
QuikSCAT	NASA		Ocean surface winds
SAC-C	CONAE/NASA	Argentina	Atmospheric temperature
SORCE	NASA		Solar irradiance
Terra	NASA		Weather & environment
TRMM	NASA	Japan	Rainfall, lightning, storm structure
UARS	NASA	UK, Canada	Stratospheric winds and temperature

Table 4: Currently Deployed U.S. Weather-Related Satellites

The listing of deployed Earth observing capabilities above is not exhaustive. Inventories of those capabilities are available from every agency listed in Section 2. For example, NOAA completed its baseline observing system architecture (including an inventory of observing systems) in early 2003. NOAA published *its Strategic Direction for NOAA's Integrated Global Environmental Observation and Data Management System* in July 2004 (available at http://www.nosc.noaa.gov), which contains a catalog of NOAA's observing systems. NASA has a detailed description of its Earth observing systems within its Destination Earth website (http://www.earth.nasa.gov).

4. Major Gaps and Challenges

Major gaps affecting weather forecasting improvements exist in two broad areas: exploiting weather information that currently exists and improving that existing information. Exploiting existing weather information is a particular problem for developing countries, which often lack communication mechanisms to properly receive and act on that information. Additionally, there is a short fall in education and training processes and resources needed to sustain the development and use of existing weather information capabilities in those developing countries.

Within these two broad areas, there are five sub-categories of gaps in weather information that can be addressed by the U.S. Integrated Earth Observation System:

- Observational. As previously stated, lack of complete global observational coverage of the atmosphere, land and oceans (e.g., poor resolution, inadequate quality) inhibits development and exploitation of extended range products. Table 5 illustrates the following critical atmospheric parameters not adequately measured by current or planned observing systems: wind profiles; vertical profiles of moisture; precipitation; thermal profiling of the ocean mixed layer; soil moisture; surface pressure; and snow equivalent water content.
- Modeling. Inadequate aspects of scientific modeling (data assimilation, numerical weather prediction, and statistical post processing) limit the accuracy and reliability of weather forecasts and warnings. NWP models have gaps in the following categories of data that increase uncertainty and reduce model accuracy: vertical profiles of moisture flux; coverage of tropical land areas and ocean areas; measurements of clouds, precipitation, and ozone; rigorous calibration of remotely sensed radiances.
- Decision Support Tools. Decision analysis in disparate areas needs more than an accurate weather forecast. Techniques are needed to tailor those forecasts to specific applications to achieve full value (may lie outside the charter of the U.S. Integrated Earth Observation System).
- Information Technologies. Telecommunication and computer processing gaps limit observations exchange, scientific collaboration, and dissemination of critical information to decision-makers and people. Also, full implementation of new observing systems technologies is challenging due in part to a lack of structure to facilitate transition of research technologies to operational use in all components of the end-to-end weather information services system.
- Education and Training. With improvements in all facets of producing and delivering weather information, parallel improvements in education and training processes are necessary to ensure full user exploitation of that information.

The WMO has developed an international strategy to address the above-listed gaps [15]. The U.S., through the implementation of the U.S. Integrated Earth Observation System Strategic Plan, is now poised to develop a national strategy to address these same gaps.

Variable	**Warnings and Nowcasts (0-1 day)**	**Short-range Forecasts (1-3 days)**	**Medium-range Forecasts (3-5 days)**	**Long-range Forecasts (5-15 days)**
Aerosol profile	4	4	4	4
Air pressure over land and sea surface	1	1	1	2
Air specific humidity (at surface)	1	2	3	3
Air temperature (at surface)	1	1	1	4
Atmospheric stability index	1	1	2	2
Atmospheric temperature profile	1	1	2	4

Cloud base height	2	3	3	4
Cloud cover	1	1	1	1
Cloud drop size (at cloud top)	4	4	4	4
Cloud ice profile	2	3	4	4
Cloud imagery	1			
Cloud top height	1	2	3	4
Cloud top temperature	1	2	3	4
Cloud type	1	3	4	4
Cloud water profile	2	3	4	4
Dominant wave period and direction	2	2	3	3
Fire area and temperature	2	3	4	4
Height of top of the Planetary Boundary Layer	2	3	4	4
Height of tropopause	2	3	4	4
Land surface temperature	1	1	2	3
Leaf Area Index (LAI)	2	2	2	2
Long-wave Earth surface emissivity	1	2	3	4
Normalized Differential Vegetation Index (NDVI)	2	3	4	4
Ocean currents (vector)	3	3	4	4
Outgoing long-wave radiation at TOA	2	2	3	4
Outgoing short-wave radiation at TOA	2	2	3	4
Ozone profile	3	3	4	4
Precipitation index (daily cumulative)	2	3	4	4
Precipitation rate (liquid & solid) at the surface	2	3	4	4
Sea surface bulk temperature	1	1	2	3
Sea-ice cover	1	1	2	3
Sea-ice surface temperature	4	4	4	4
Sea-ice thickness	3	4	4	4
Significant wave height	1	2	3	4
Snow cover	1	3	4	4
Snow water equivalent	3	3	4	4
Soil moisture	2	3	3	4
Specific humidity profile	2	3	4	4
Temperature of tropopause	2	3	4	4
Wind profile (horizontal & vertical components)	3	4	4	4
Wind speed over land & sea surface (horizontal)	2	2	3	4

TABLE KEY:
1 Possible and available today
2 Not yet available, but possible in 2 years (existing systems)
3 Not yet available, but possible in 6 years (existing and new systems)
4 Not yet available, but possible within 10 years if work is started now

Table 5: Capability to Observe Environmental Parameters (WMO)

A recent article, reporting on a national workshop to develop an implementation plan for the USWRP, listed warm-season quantitative precipitation forecasts as the poorest performance area of forecast systems worldwide [16]. This report illustrates the gaps and challenges facing the national and international weather forecasting communities. Key gaps were found in understanding key scientific processes, observations, and data assimilation.

- Scientific processes-. Knowledge of environmental aerosols may prove necessary for properly representing cloud microphysical processes, but there are no efforts underway to provide routine observations of aerosols or even to provide a systematic research assessment of the forecast sensitivity.
- Observations- Observations on the scale of the events being forecast (e.g., summer thunderstorms) are limited to those available from surface mesonets, profilers, radars and geostationary and GPS satellites. While useful, these observing systems do not provide certain key pieces of information required by models. For example, the quality and vertical resolution of geosynchronous satellite data over heterogeneous continental backgrounds remains unacceptably low, distant radars overshoot the boundary layer, nearby radars leave a "cone of silence" and surface mesonets provide no information about the free troposphere unless augmented with profiling devices.
- Data assimilation- In the overall process of forecasting convective precipitation, data assimilation may be the most critical path through which the pace of forecast advances will be modulated. Two glaring gaps exist here. First, there is a serious deficiency in human resources working on data assimilation. Second, a large fraction of current observations are not being assimilated into today's models.

To address these challenges, the USWRP recommends a tightly knit implementation plan addressing basic research, advanced development (observations, assimilation technologies, and forecast systems), and experimental forecast demonstrations (with emphasis on societally grounded verification metrics).

5. Future Earth Observation Systems that May Fill Gaps

Vision The following illustration (scenario or "use case") provides one view of the benefits possible from improving weather forecasting through a U.S. Integrated Earth Observation System. One can certainly develop similar views for other regions or for global application.

> *Ten years from now a weak tropical storm forms in the Caribbean Sea. In situ AMDAR measurements from commercial aircraft and space-based hyperspectral sounders and NPOESS instruments provide atmospheric and oceanic environmental data to advanced numerical prediction models. These models predict a high probability of a minimum-intensity hurricane with great rainfall potential making landfall along the coasts of Honduras and Guatemala days hence. Other space-based sensors detect abnormally high soil moisture along northern slopes of the Honduran and Guatemalan highlands. Using these soil moisture data and numerical rainfall predictions,*

> *hydrologic models predict massive run-off, flooding and high probability of mudslides for a 300-km band of the highlands 18-24 hours following landfall. Global weather and hydrological predictions are transmitted from the U.S. National Weather Service to a new regional environmental prediction and warning center, established to serve Central American nations. With expertise on local conditions, the regional center issues warnings 4 days in advance, allowing decision makers, relief agencies and inhabitants to take action. As predicted the storm barely reaches hurricane strength, but following landfall rain totals exceed 25 cm in 6 hours over the higher elevations. Rampaging rivers subsequently uproot trees and destroy many hundreds of homes, but thousands of lives and much property are saved by the ample warnings.*

Given this scenario, one envisions that every country will have the weather information needed to virtually eliminate loss of life and to strongly reduce property damages from severe weather events. For developing countries, the reduction of impacts could reach that attained in developed countries over the past decades.

One envisions an end-to-end weather information system that provides, to decision makers around the world, timely, reliable and actionable information prior, during and after the event for relief support. This system will have the following improved capabilities:

- Improved *in situ* and remotely-sensed observations of critical parameters, coordinated and exchanged globally, providing input to
- Improved numerical prediction models, with advanced physics capabilities, providing accurate (in location and time) forecasts of severe weather events to
- New or strengthened regional and local warning centers, allowing rapid and tailored notification to local authorities responsible for protecting people and property.

One envisions societies where weather forecasts are fully used in decision support systems to improve economic efficiency and productivity, as well as environmental protection, through improved longer-range predictions available in probabilistic terms.

Transitioning Research to Operations

To attain the benefits "foreseen" above requires a substantial increase in current weather forecasting capabilities. The key to increasing those capabilities is to field new capabilities that, if existent, are presently in some stage of research or development (transitioning research to operations). A recent NRC study [20] addresses this topic, noting the weaknesses in current transition pathways and processes and providing recommendations for improvement. The report describes the transition process as one that involves a "push-pull" dynamic in which research and technology development programs respond to the requirements (pull) of the operational user and the operational system takes advantage of new research results and technologies (push) that emerge as a result of science and technology evolution. User requirements and priorities were discussed in Section 4. Research activities are discussed below which, upon successful transition, provide an opportunity for improving weather forecasting capabilities.

NWS has published two plans that form the basis of improving weather information within the U.S.—the NWS Science and Technology Infusion Plan (STIP) and the NWS Service Improvement Plan (NSIP—2004). The NWS STIP: looks into the future and explains how science and technology may evolve NWS products and services; defines long term strategies, objectives, and programs; and illustrates how the NWS plans to take advantage of scientific opportunities beyond the next ten years [21]. The NSIP—2004 translates the grand vision of the NWS STIP into specific customer service improvements in the areas of aviation, climate, fire weather, hydrology, marine weather, health (e.g., air quality), and homeland security [22]. Figure 3 (taken from the NWS STIP) illustrates the NWS science and technology plan for monitoring and observing. The bulleted items are advances NWS plans to pursue to improve capabilities over the near-, mid- and far-term of the next decade.

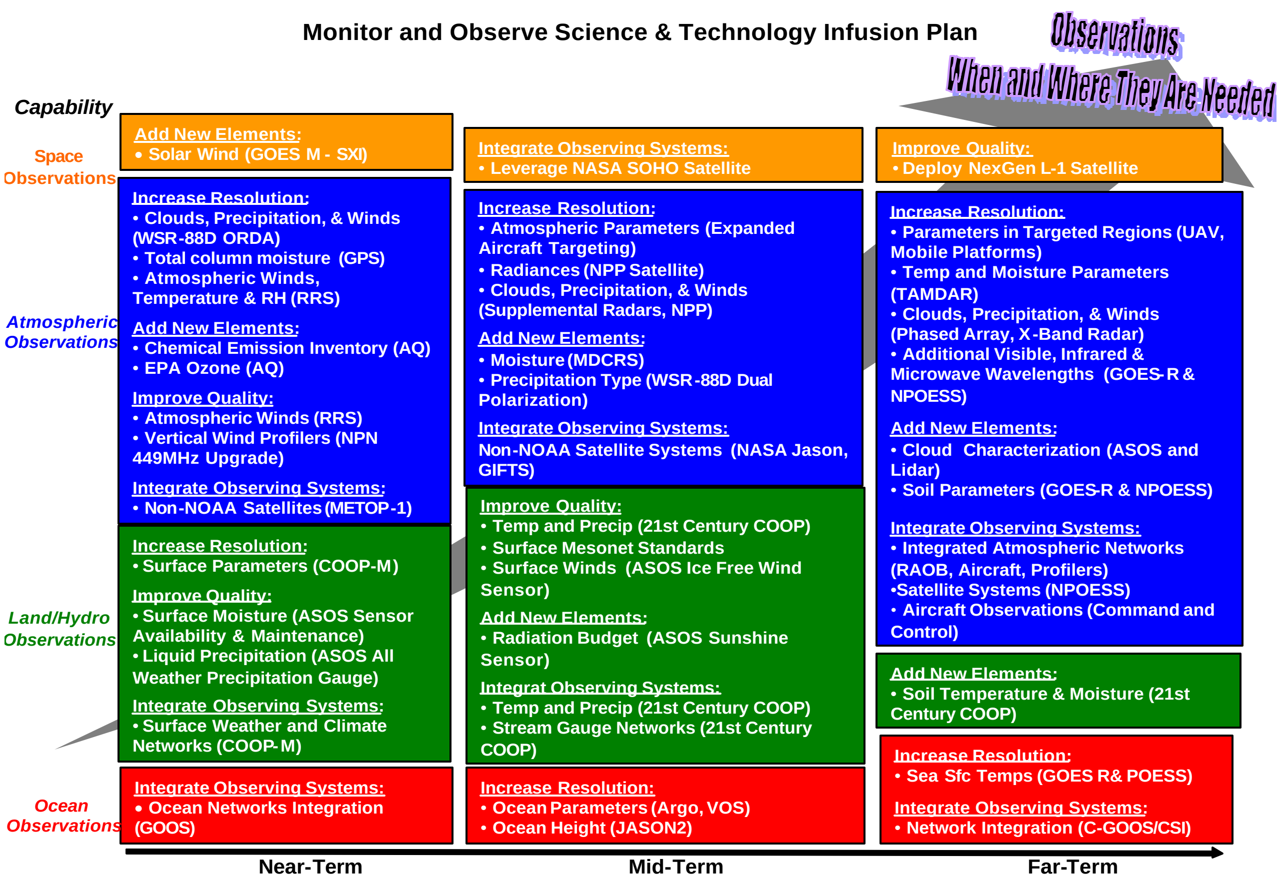


Figure 1. Monitor and observe science and technology infusion plan. Bulleted items are advances NWS will pursue to improve capabilities (denoted by color) over near-, mid-, and far-term time periods of the next decade. Objectives (see text for definitions) are underlined, items in parenthesis denote specific programs (see acronym list for definitions).

Figure 3: National Weather Service Monitor and Observe Science Technology Infusion Plan

There are several collaborative research and development activities focused on improving operational weather forecasting capabilities.

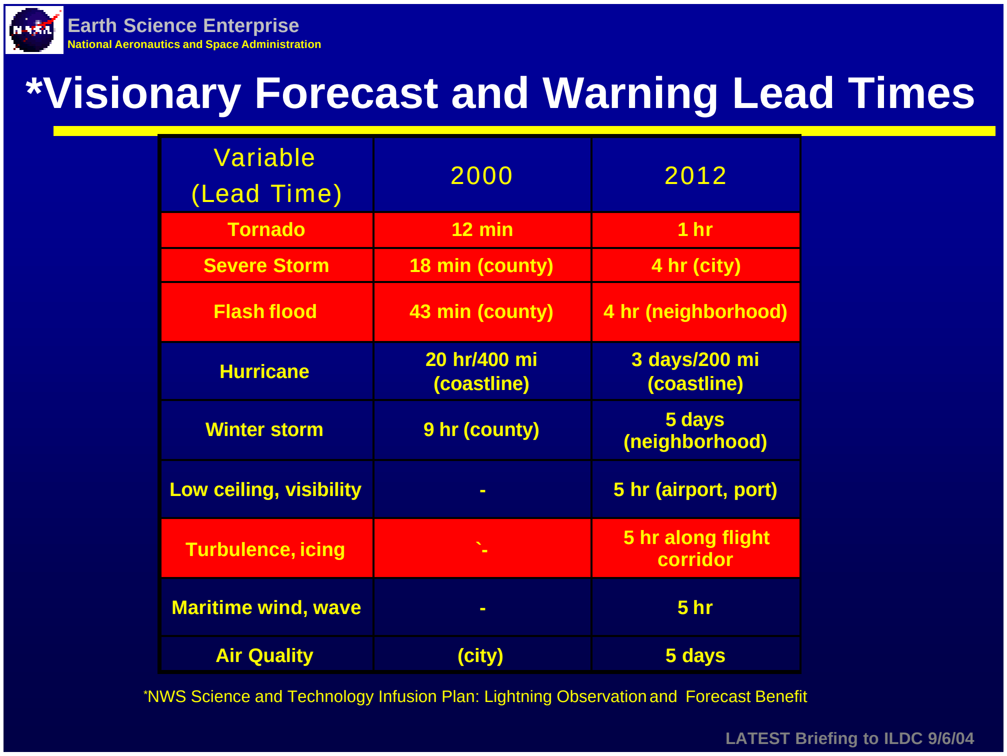
First, through the Joint Center for Satellite Data Assimilation (JCSDA), NOAA, NASA, and DoD are developing common NWP model and data assimilation infrastructure for:

- Accelerated development of assimilation algorithms for current operational satellite soundings from GOES, POES and DMSP
- Rapid assimilation of programmed operational (CrIS, ATMS and VIRS on NPOESS) and research satellite data (from QuickSCAT, TRMM, and MODIS) into operational models

Second, NOAA is working with NASA's Short-term Prediction Research and Transition (SpoRT) Center to accelerate the infusion of NASA science and technology to help meet Weather Forecast Office (WFO) needs for improved:

- Aviation forecasts
- Specification of convective initiation and evolution
- Specification of precipitation type
- Prediction of precipitation amounts and areal extent

SpoRT helps fill gaps in the NWS STIP, maps regional NWS WFO priorities to SpoRT research capabilities, prepares field offices for new forecasting tools (risk reduction), provides required training and develops assessment strategies. Figure 4 provides a vision of the improved forecast and warning lead times available as a result of effective NOAA/NASA collaboration through SPoRT.



Variable (Lead Time)	2000	2012
Tornado	12 min	1 hr
Severe Storm	18 min (county)	4 hr (city)
Flash flood	43 min (county)	4 hr (neighborhood)
Hurricane	20 hr/400 mi (coastline)	3 days/200 mi (coastline)
Winter storm	9 hr (county)	5 days (neighborhood)
Low ceiling, visibility	-	5 hr (airport, port)
Turbulence, icing	`-	5 hr along flight corridor
Maritime wind, wave	-	5 hr
Air Quality	(city)	5 days

Figure 4: National Weather Service Envisioned Weather Forecast Capabilities in 2012

Third, NASA has a Weather Research Roadmap, which is a combined vision of NASA, NOAA and the research community. This Roadmap outlines recommended steps to help the nation achieve improvement in near-, mid- and far-term forecasts using NASA's latest data and modeling research. The Roadmap sets weather forecast improvement goals, identifies key steps to achieve those goals, identifies enabling research for improved weather forecasts, and links this weather program implementation plan to the NASA Earth Science Enterprise research strategy. Figure 5 illustrates some key steps and a notional schedule for this plan.

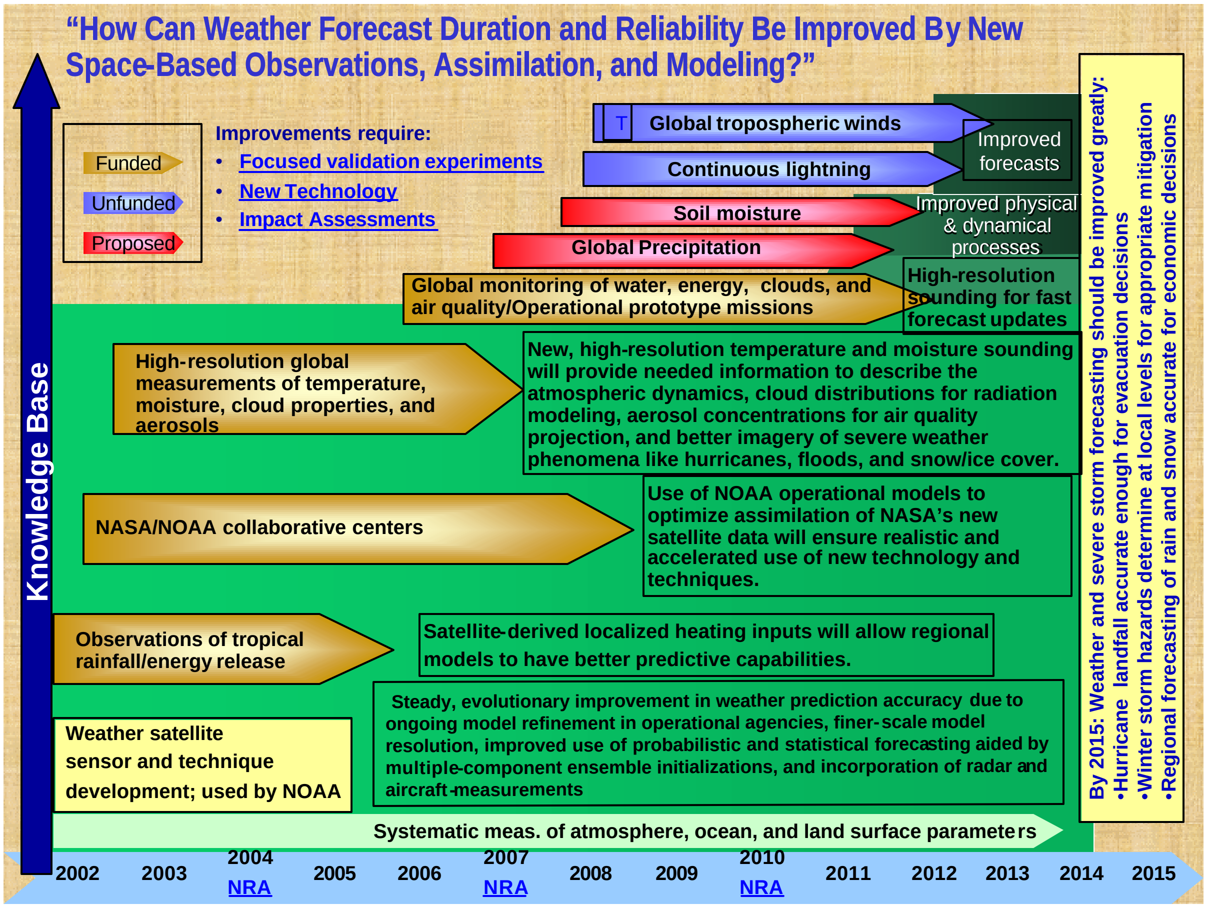


Figure 5: NASA Weather Research Plan for Improving Weather Forecasting

Fourth, the FAA Aviation Weather Research Program (AWRP) is striving to increase scientific understanding of atmospheric conditions that cause dangerous weather impacting aviation. The research is aimed at producing weather observations, warnings, and forecasts that are more accurate and more accessible. Within the AWRP, FAA partners with NOAA, DoD, the National Center for Atmospheric Research, and the Massachusetts Institute of Technology's Lincoln Laboratory (MIT LL) to develop product development teams (PDTs). These PDTs are teams of scientists from the partner organizations who work together to solve aviation problems caused by weather. Teams are currently organized to address the following topics: in-flight icing, aviation forecasts, forecast quality, turbulence, winter weather, convective weather, terminal and national ceiling and visibility, model development and enhancement, advanced weather radar techniques, and oceanic weather.

Fifth, through USWRP, federal agencies are partnering with universities and other research institutions to mitigate the effects of weather disasters (such as hurricanes) and to improve predictions of precipitation and flooding. Four current USWRP initiatives promise immediate benefits to national security, energy, and the economy [23]:

- The Weather Research and Forecasting model (WRF) will be used by both researchers and forecasters, putting research improvements into immediate operational use. With USWRP and other funding, a prototype has been developed and is currently being tested. WRF is a collaborative effort among a number of government agencies and universities.
- The Hemispheric Observing System Research and Predictability Experiment (THORpex), a major international field experiment over the Pacific Ocean, will improve two- to ten-day forecasts for U.S. regions and urban areas. THORpex is planned for 2003-2010, and involves dozens of institutions, and researchers and operational meteorologists from 14 nations in the Northern Hemisphere.
- Operational testbeds will evaluate new weather prediction models and new forecasting techniques without interfering with the day-to-day operation of forecast centers. Two testbeds are currently being developed—one for hurricane predictions and another for modeling improvements.
- Short-term forecasting improvements will focus on a few hours out to two days and will improve predictions of severe storms, distribution of precipitation, temperature, and air quality.

This is not an exhaustive list of research programs, but illustrates the national focus on improving weather forecasting to benefit society.

Planned Programs Two new operational weather satellite systems – NPOESS and GOES-R – will replace NOAA's current polar and geostationary satellites in 2009 and 2012, respectively. Both will provide improved technologies to support the detection and monitoring of severe weather, tropical cyclones, volcanic eruptions and ash clouds. These instruments will have improved spatial and temporal resolution, and will include a wider range of spectral bands than current POES systems, although some bands currently available and used for fire detection will either be absent or too sensitive on the NPOESS equivalent for fire detection in daytime.

National Polar-orbiting Operational Environmental Satellite System (NPOESS). In 1994, it was recognized that converging the existing polar-orbiting weather satellite systems from the Department of Commerce (DOC) and Department of Defense (DoD) would result in a more cost effective and higher performance integrated system. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) is that system. The tri-agency Integrated Program Office (IPO), utilizing personnel from the Department of Commerce, Department of Defense and NASA, manages the NPOESS program. NPOESS is a satellite system used to monitor global environmental conditions, and collect and disseminate data related to weather, atmosphere, oceans, land and the near-space environment. These three agencies serve as the program directorates. The DOC (through NOAA) has overall responsibility for the program, as well as for satellite command, control and communications operations. The DoD (through the Air Force) has the primary responsibility to acquire and support the converged satellites. NASA has lead responsibility for facilitating development and insertion of new cost-effective technologies that may enhance the ability of the converged system to meet its operational requirements. By converging U.S. polar-orbiting satellite programs (e.g. POES and DMSP), the NPOESS will reduce the number of polar-orbiting systems from four U.S. satellites to three. NPOESS goals include the incorporation of new technologies from NASA and encouragement of international cooperation. The current NPOESS mandate extends to the year 2018. In addition to cost-effectiveness the National Polar-orbiting Operational Satellite System (NPOESS) increases the timeliness and accuracy of severe weather event forecasts. Advanced microwave imagery-sounding data products will lead to improved prediction of ocean surface wind speed and direction, a major factor in the phenomenon we call weather. The knowledge obtained from NPOESS data reduces the potential loss of human life and property resulting from severe weather. An improved hurricane landfall forecast skill will save an estimated $1 million per mile of coastline that does not have to be evacuated. Support for general aviation, agriculture, and maritime activities aimed at improved early warnings will mitigate the devastating effects of floods through disaster planning and response. NPOESS will be instrumental in helping the military shift its tactical and strategic focus from "coping with weather" to anticipating and exploiting atmospheric and space environmental conditions (http://www.npoess.noaa.gov).

Geostationary Operational Environmental Satellite System-R (GOES-R). The Geostationary Operational Environmental Satellite, or GOES-R, to be launched in 2012, will provide critical atmospheric, oceanic, climatic, solar and space data. The satellite will house an advanced imager, hyperspectral suite (including atmospheric sounding and coastal waters capabilities), lightning mapper, solar imager and space environment monitor. This new GOES, planned for launch in 2012, will scan the Earth nearly five times faster than the current GOES. The satellites will provide the user community (television meteorologists, private weather companies, the aviation and agriculture communities, and national and international government agencies) with about one hundred times the amount of data currently provided (http://www.osd.noaa.gov).

Table 6 presents all planned U.S. weather satellite systems, both operational and research:

Mission	**Organizations**	**Associated Countries**	**Environmental Parameters**
Aquarius	CONAE/NASA	Argentina	Ocean salinity
CALIPSO	NASA/CNES	France	Clouds & aerosols
Cloudsat	NASA		Cloud structure
Glory	NASA		Aerosols & volcanic plumes
GOES-R series	NOAA/NASA		Weather
GPM Core	NASA/JAXA	Japan	Precipitation
Hydros	NASA/ASI/CSA	Italy, Canada	Soil moisture
NPOESS series	NOAA/DoD/NASA		Weather & environment
NPP	NASA		Weather & environment
ROCSAT-3/COSMIC	NSPO/UCAR/NASA	Taiwan	Atmospheric temperature

Table 6: Currently Planned U.S. Weather-Related Satellites

Other weather-related future solutions include:

- Global expansion of the commercial aircraft Meteorological Data Collecting and Reporting System (MDCRS) and more use of local carriers;
- Expanded deployment of surface-based radar wind profilers to observe the atmospheric boundary layer;
- Enhancement of the NWS upper air network with GPS accuracy;
- Development and deployment of arrays of phased-array radars to significantly increase the quantity, quality and timeliness of weather information in extreme weather;
- Operational deployment of high-altitude UAVs such as NASA's Global Hawk.

Most important is the need to integrate these observations to make optimum use of each and enhance information content.

Time table The vast number of weather forecasting advancements and improvements referred to above will likely occur over time. The schedule below provides a rough near-, mid- and far-term view of "what needs to be done and when" to attain the capabilities envisioned in the scenario described above.

Two-year time frame:
Initial investments in critical data gaps (e.g., atmospheric wind and humidity profiles, and soil moisture) and improved predictive models will augment the quality of forecasts of severe events and general weather conditions; greater sharing of these forecasts with developing countries will reduce impacts on life and property.

Six-year timeframe:
Further improvements in data and models will allow the production of reliable forecasts of severe weather, i.e. forecasts that include reliability/probability estimates as well as range of possible outcomes. This improved information will be used by newly established regional and local warning centers that will interact with local authorities and provide them tailored guidance. In addition, these new products and services will find great applications to support economic growth and sustainable development.

Ten-year timeframe:
Full-fledged system will provide local authorities all the weather information they need to eliminate loss of life and greatly reduce property damage.

6. Interagency and International Partnerships

Partnerships at government, academic and private sector levels are key for engendering the socioeconomic benefits of improved weather forecasting. A recent document by the National Academy of Sciences states “without a strong, effective collaboration among the government, academic, and private sectors, the general public would not have been the beneficiary of the great advances in weather and climate science and technology over the last 50 years” [17]. Various types of partnerships described below address aspects of observation, exploitation and dissemination.

Government-academic partnerships are necessary in order to have a strong scientific component in the national weather program. Many government-academic partnerships involve state and local agencies that are beneficiaries of improved capabilities. A strong partnership exists between the government and the media in providing weather warnings to the public, especially during life-threatening events. Private sector companies have also responded to such government-private sector partnerships by developing communications technologies and systems for tracking storms and tornadoes.

Academic-private sector partnerships reflect the fact that the work force today and in the future requires highly educated graduates with increasingly diverse skills. In addition to their “traditional” knowledge skills, meteorologists will need greater familiarity with economics, social science and/or specific industries (e.g., agriculture, health care, transportation, energy). By stimulating interaction among teachers, researchers and students at universities with forecasters and other professionals in the government and private sectors, cooperative programs should help meet the demand for a broadly trained and flexible work force [18].

Finally, in some cases all three sectors may cooperate because each has an interest in a particular improvement or because the expertise of all three sectors is required to address the problem and present opportunities for government-private-academic sector partnerships. Examples of successful partnerships are cited by NAS [19], and include the collocation of new weather service offices in academic research environments, the NWS cooperation with military and emergency responders under the Homeland Security Initiative, programs at the University Corporation for Atmospheric Research (UCAR), and advances to NEXRAD.

Table 7 illustrates some of the key weather partnerships nationally and internationally. OFCM coordinates the Federal Committee for Meteorological Services and Supporting Research activities. The Operational Processing Centers partnership is coordinated through OFCM and emphasizes common approaches to better data assimilation, numerical weather prediction (NWP), and product and service development and delivery within the major governmental NWP centers.

The Applied Meteorology Unit (AMU), collocated with the U.S. Air Force Range Weather Operations flight at Cape Canaveral Air Force Station, is a technology transition organization jointly funded and supported by DoD, NASA and NOAA. The AMU is a “transition of research to operations” success story”, ensuring the sustainment of high quality operational weather forecasting support to the NASA Space Shuttle program and launches from the Air Force’s Eastern Range. The National Ice Center, a joint activity of the U.S. Navy (DoD), NOAA, and the U.S. Coast Guard (DHS), provides operational ice analyses for sea and lake ice for the Great Lakes and U.S. coastlines. The U.S. is an active partner with WMO and the World Weather Watch. In fact, the *Federal Plan for Meteorological Services and Supporting Research* addresses individual agency participation in WWW activities annually. The Joint Center for Satellite Data Assimilation is a virtual center, comprised of NASA, NOAA and DoD scientists, established to facilitate the use of satellite environmental data by developing new and powerful mathematical techniques to assimilate the data into numerical weather prediction models.

PARTNERSHIPS	PARTICIPATING AGENCIES
Federal Committee for Meteorological Services and Supporting Research	OSTP, DOC, USDA, DoD, DOE, DOI, DOS, OMB, DOT, DHS, NASA, NTSB, EPA, NSF, Nuclear Regulatory Commission
U.S. Weather Research Program	NOAA, NSF, NASA, DoD, DOT, DOE, USDA, NCAR, American Meteorological Society
Operational Processing Centers	NOAA (NCEP), U.S. Air Force, U.S. Navy
Applied Meteorology Unit	DoD, NASA, NOAA
National Ice Center	DHS, DoD, NOAA
World Meteorological Organization	186 countries throughout the world
Joint Center for Satellite Data Assimilation	DoD, NASA, NOAA

Table 7: Key National and International Weather Partnerships

7. U.S. Capacity Building Needs

Operational weather data are among the most valuable Earth observation capacities that nations can have. Each year hazardous weather and floods kill tens of thousands of people and cause many billions of dollars in infrastructure damage. Such losses have already been reduced substantially in developed countries through use of Earth observations to produce timely, accurate forecasts and warnings. Creating greater capacity to observe the global environment is fundamental to building more accurate forecasts and extending this capability to developing nations.

In countries where limited or no operational weather capability exists, priority needs include partnering with developed nations for access to high-cost weather data and prediction services; partnering with neighboring nations to develop and deliver regional warnings; and local education and training for use of warnings by decision makers and the public so they can most effectively and efficiently exploit existing weather information services worldwide.

Expansion of observing capacity is needed to detect precursor environmental conditions that constitute the foundation for improving all weather and climate services, as called for in the WMO World Weather Watch Plan. Highest priority should be given to filling gaps in the *in situ* and space-based observation capacity that limits data assimilation and predictive capabilities. Additionally, emphasis is needed on open global sharing of data. Next, these data must be exploited through better research, advanced data assimilation and predictive models, building telecommunications infrastructure capacity, and transforming weather predictions into formats understandable to decision makers and the public.

Needs for building capacity in the U.S. can be identified in part from existing strategic and roadmap documents. These needs include:

- Developing technologies that enhance systems for observing weather phenomena and for assimilating and analyzing resulting data.
- Maintaining a research staff of sufficient size and expertise at national weather centers to develop new forecast techniques and products.
- Working with the academic community to improve weather prediction models.
- Developing and maintaining the capability to test and evaluate new algorithms and forecast models in parallel with operational systems.
- Obtaining feedback from the user community (e.g., agriculture, transportation, insurance, emergency managers, the media and the general public).
- Securing sufficient budgets to develop necessary algorithms to allow the introduction of new sensors into operational systems, and assigning the responsibility for technology transitions.
- Providing for adequate computer resources, including parallel processing and efficient code development, and model archiving systems.
- Developing personnel with proper understanding of user needs, as well as technological capabilities, including communications expertise.
-

NWS forecast and warning services will be an essential component of the information on weather, climate, hydrology, space weather, air quality and other environmental factors used by the expanded provider network to serve a variety of socioeconomic needs.

8. Conclusions

From an international to a local perspective, improving the accuracy, timeliness, and reliability of weather information is critically important. Gradually, more nations are recognizing the societal benefits to be gained through Earth observations and the efficiencies to be realized by working together. Within the U.S., an Integrated Earth Observation System will help realize those efficiencies

For the U.S., there is synergy between improving weather forecasting and the development of an Integrated Earth Observation System. Cooperation among weather forecasting agencies, on the national and international level, is a benchmark for other Earth observation communities. Weather forecasters have made significant progress in establishing common requirements across the spectrum of users (public and private sectors and academia). Improvements in weather forecasting capabilities have been dramatic over the past 20 years, but much still needs to be done to meet users' expectations. Continued weather forecasting improvements and a sustained weather information infrastructure will depend on effective partnerships, implementing appropriate components of existing plans, and developing and implementing the Integrated Earth Observation pathway forward.

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