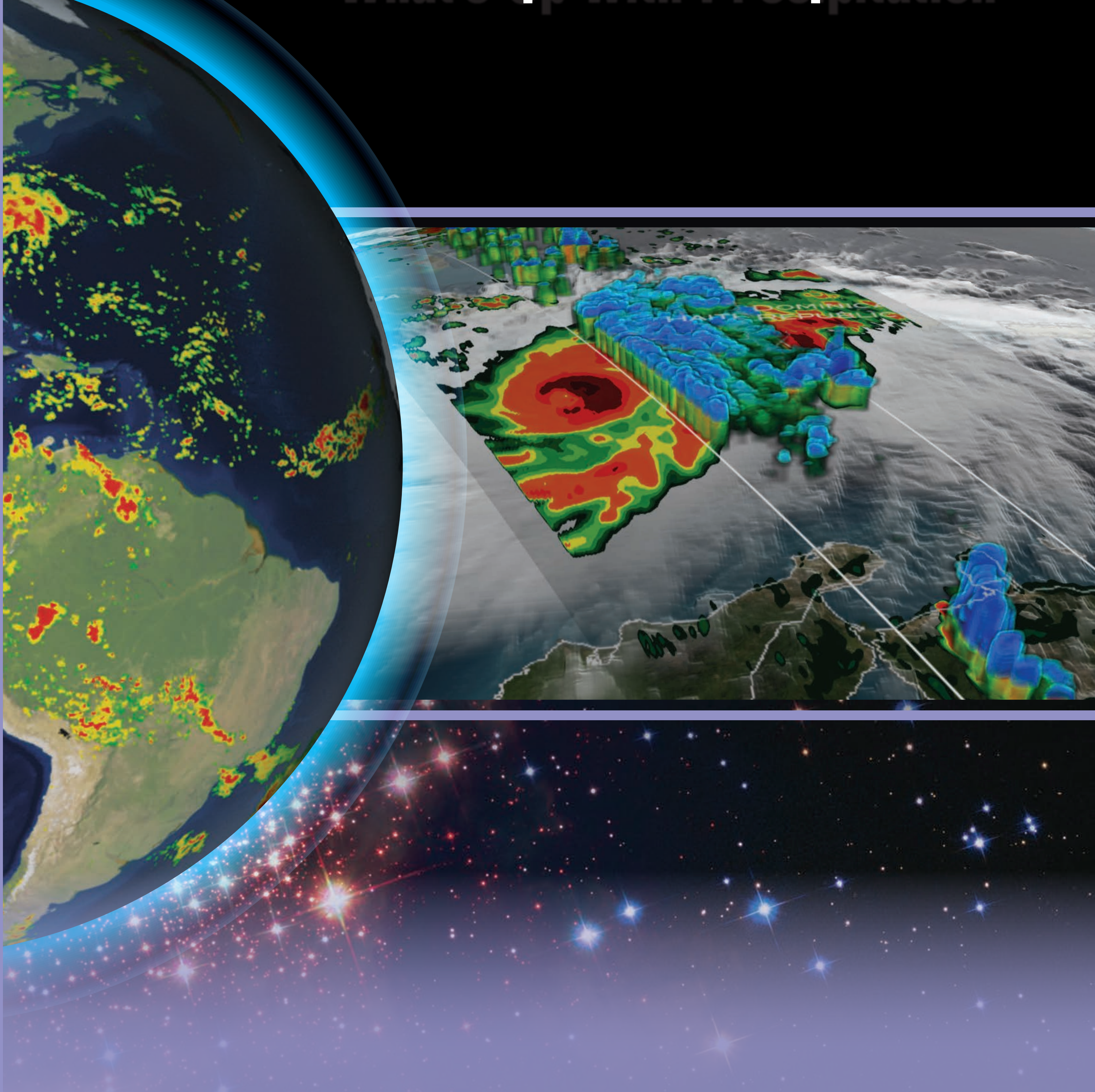
National Aeronautics and
Space Administration

Understanding Earth
What's Up with Precipitation?



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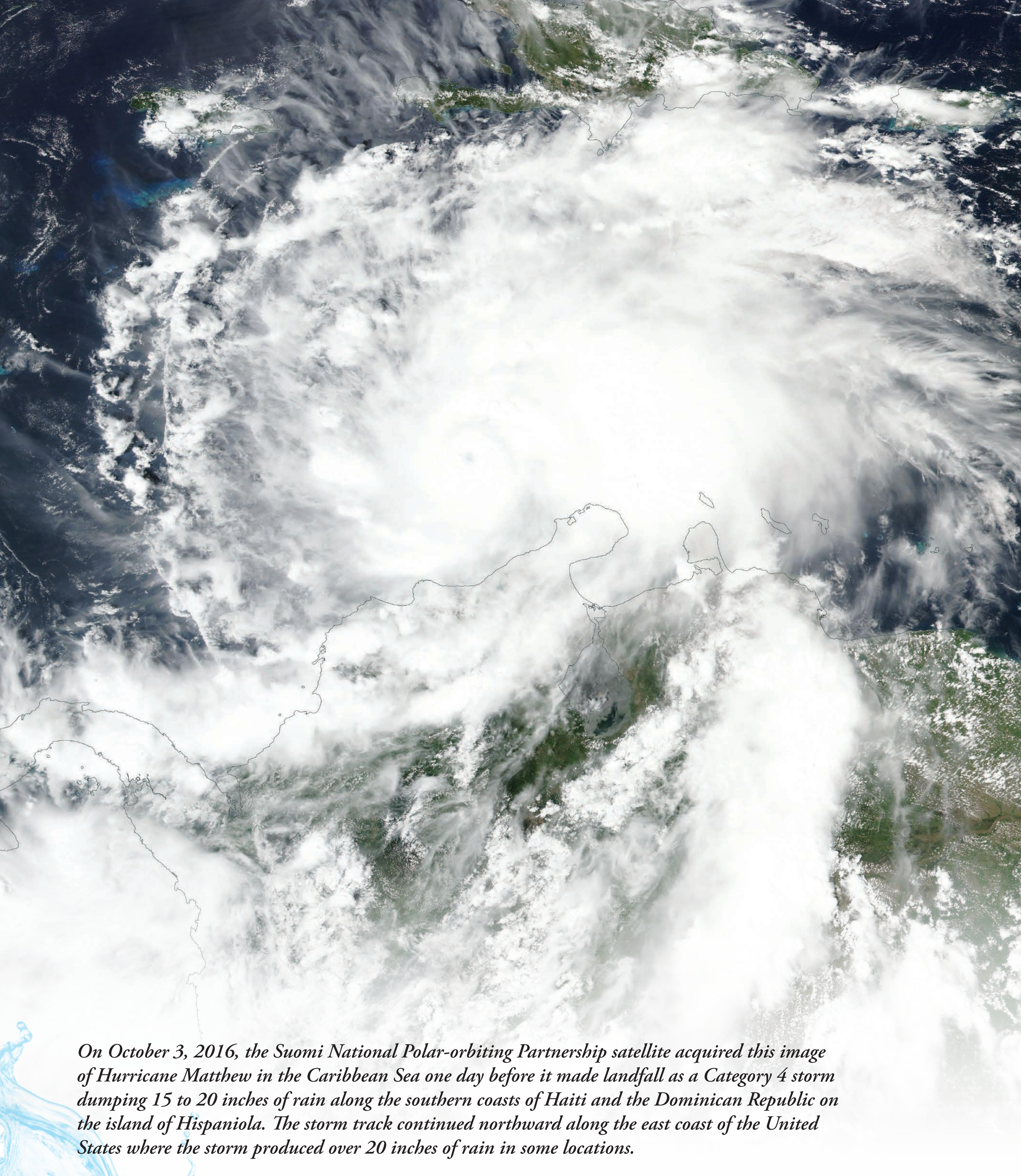
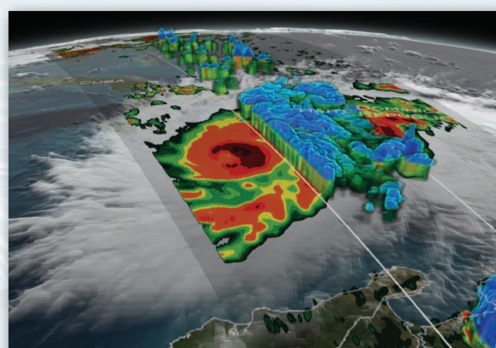
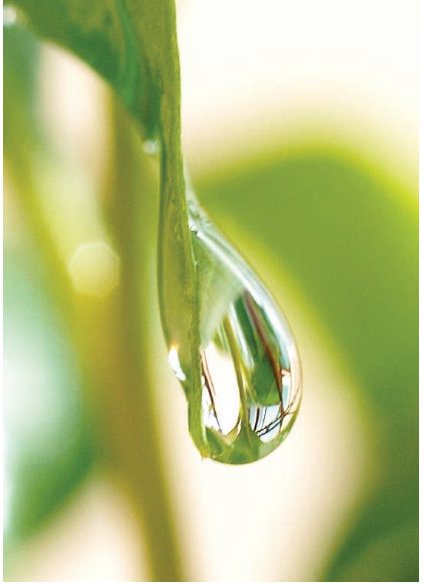


On October 3, 2016, the Suomi National Polar-orbiting Partnership satellite acquired this image of Hurricane Matthew in the Caribbean Sea one day before it made landfall as a Category 4 storm dumping 15 to 20 inches of rain along the southern coasts of Haiti and the Dominican Republic on the island of Hispaniola. The storm track continued northward along the east coast of the United States where the storm produced over 20 inches of rain in some locations.

UNDERSTANDING EARTH: What’s Up with Precipitation?



On the cover: On October 3, 2016, NASA’s Global Precipitation Measurement Core Observatory satellite flew over Hurricane Matthew and captured this three-dimensional view. Blue and purple shades indicate frozen precipitation, while green, yellow, and red shades indicate light to heavy liquid precipitation.



[Above] *Water is a molecule that is composed of two hydrogen atoms and one oxygen atom, or H_2O. While it seems like a relatively simple compound, a tremendous amount of energy is needed to bond these atoms together. The very water we drink and brush our teeth with today was originally created during a supernova explosion that happened billions of years ago—even before Earth was formed.*

Earth's Water and the Role of Precipitation

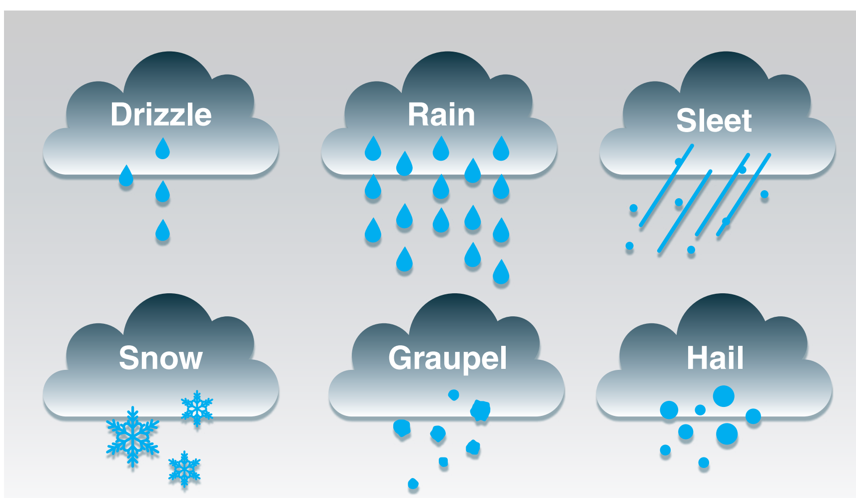
Water—the main reason for life on Earth—continuously circulates through one of Earth's most powerful systems: the water cycle. Water flows endlessly between the ocean, atmosphere, and land. Earth's water is finite, meaning that the amount of water in, on, and above our planet does not increase or decrease.

Of all the water that exists on our planet, roughly 97% is saltwater and less than 3% is freshwater. Most of Earth's freshwater is frozen in glaciers, ice caps, or is deep underground in aquifers. Less than 1% of Earth's water is freshwater that is easily accessible to us to meet our needs, and most of that water is replenished by precipitation—a vital component of the water cycle, affecting every living thing on Earth.

Precipitation is any product of the condensation of atmospheric water vapor that falls quickly from a cloud. The main forms of precipitation include drizzle, rain, sleet, snow, graupel (soft hail or snow pellets), and hail. While precipitation is the ultimate source of the freshwater we use in our daily lives, this essential natural resource is not distributed evenly across our planet. On land, some places are drenched with rain, such as temperate and tropical rainforests. Other locations receive little rain and snow and are so dry that communities, such as Las Vegas, Nevada, recycle water that has been used for bathing and cleaning—known as *gray water*—to water their gardens.

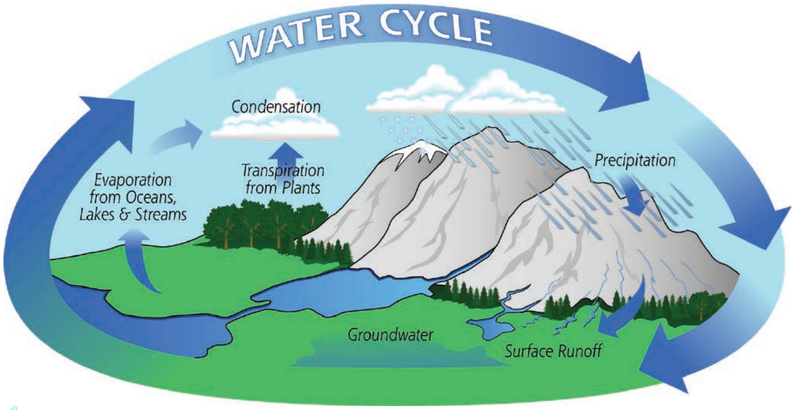
Understanding the role of precipitation in Earth's water cycle and how it interacts with other Earth systems requires a global view. The distribution of water throughout the atmosphere and how it moves, changing between its solid, liquid, and gaseous forms, is a powerful vehicle for redistributing Earth's energy and influences the behavior of the planet's weather, climate, and other environmental systems.

[Above] *Viewed from space, Earth appears as a* ***blue marble****, as approximately 73% of Earth's surface is covered by water.*



[Above] *The main forms of precipitation include drizzle, rain, sleet, snow, graupel, and hail. The ability to differentiate between these forms is important for improving weather forecasts.*

[Below] *The water cycle describes how water evaporates from Earth's surface, rises into the atmosphere, cools and condenses to form clouds, and falls again to the surface as precipitation, where it flows into the ocean, over the land surface, and underground.*



DID YOU KNOW? Water resource managers rely on accurate precipitation measurements to monitor their freshwater resources.

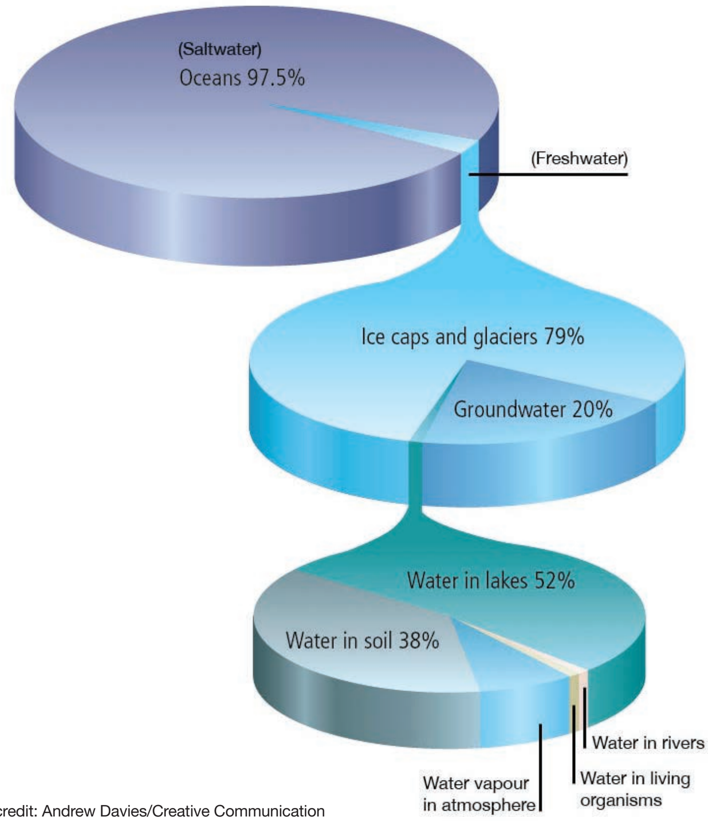


Image credit: Andrew Davies/Creative Communication

[Above] *Only a tiny portion of Earth's water is freshwater. Plants, animals, and humans all need freshwater to survive. We use freshwater for drinking water, industrial uses, to generate power, to irrigate crops, and as part of sanitation systems, to name a few.*

Photo credit: Kay Ledbetter/Texas A&M Agrilife Research

Photo credit: UK Department for International Development

Photo credit: Travis Lupick

Photo credit: Stacy Smith/Bureau of Reclamation

[Above] *For thousands of years, civilizations have tried to manage the intricate balance of having too much or too little water.*

Measuring Precipitation: On the Ground and from Space

Photo credit: Iowa Flood Center

Photo credit: Community Collaborative Rain, Hail & Snow Network

Photo credit: NASA

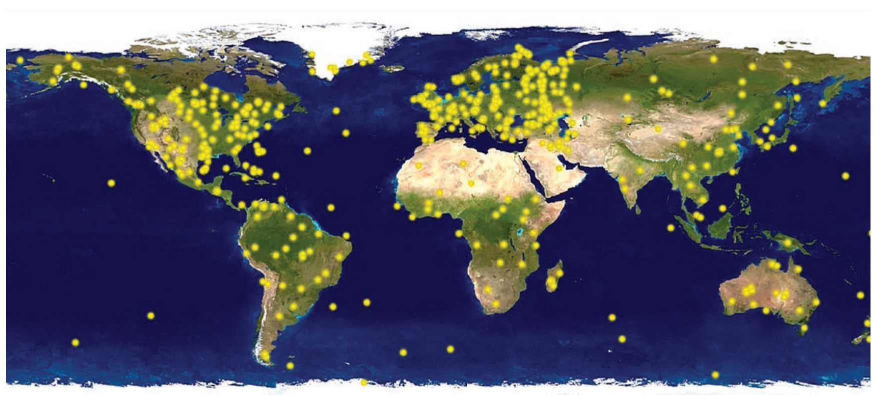
[Above] *Ground-based instruments used to observe precipitation include rain gauge tipping buckets, cylinders, and disdrometers [top]; snowboards; hail pads [middle]; and radar systems [bottom]. Snowboards and hail pads are used to measure frozen precipitation. Snowboards are used to accurately measure snow accumulation, while hail pads are used to determine the size and density of hail.*

Today, scientists can measure precipitation *directly*—using ground-based instruments such as rain gauges—or *indirectly*—using remote sensing techniques (e.g., from radar systems, aircraft, and Earth-observing satellites).

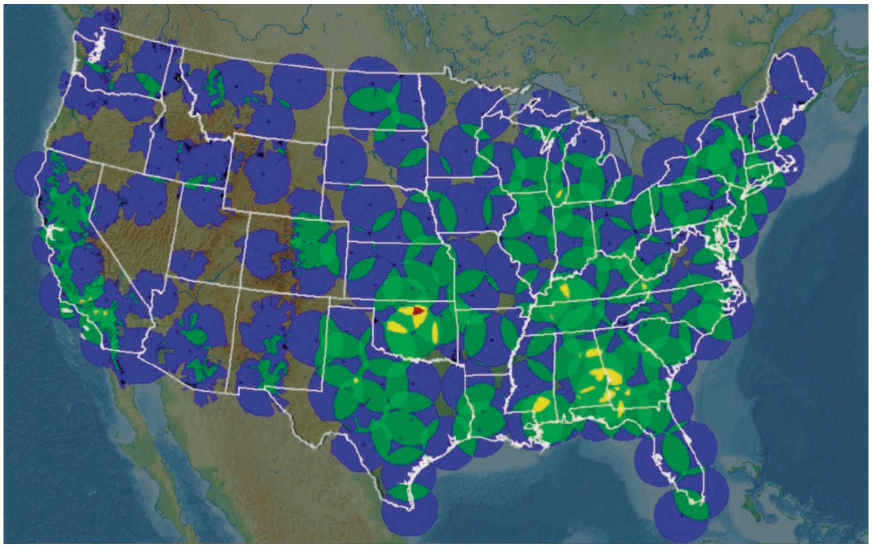
Rain gauges measure precipitation amounts at a given location. Oftentimes measurements from an individual rain gauge are used to represent precipitation conditions across larger areas, i.e., between gauge sites. However, that isn't always the best assumption. The reality is that precipitation may fall more- or less-intensely at the location of the gauge—or it may miss the gauge entirely. Damage or obstructions to a gauge or the presence of strong winds can also introduce error.

Ground-based weather radars emerged during World War II and have since been used to observe precipitation, mostly over land. Ground-based radars send out pulses of microwave energy in narrow beams that scan in a circular pattern. When the microwave pulse encounters precipitation particles in the atmosphere, the energy is scattered in all directions, sending some energy back to the radar. These measurements are used to estimate intensity, altitude, precipitation type (e.g., rain, snow, hail), and motion. Obtaining continuous measurements of precipitation from ground-based systems (e.g., from rain gauges and radar systems) presents a challenge due to large gaps between monitoring sites on land and huge gaps over the ocean.

Earth-observing satellites can provide frequent estimates of precipitation at a global scale. To do this, satellites carry instruments designed to observe specific atmospheric characteristics such as cloud temperatures and precipitation particles, or *hydrometeors*. These data are extremely useful for filling in data gaps that exist between rain gauge and ground-based radar sites and offer insights into when, where, and how much precipitation is falling worldwide. Satellite data also provide a unique vantage point. While



[Above] *This image illustrates the distribution of rain gauges around the globe. If all of the rain gauges in the world were gathered in one place, they would cover an area the size of approximately two basketball courts, or 18,800 square feet (1,740 square meters). In contrast, satellite observations from space can provide global coverage.*

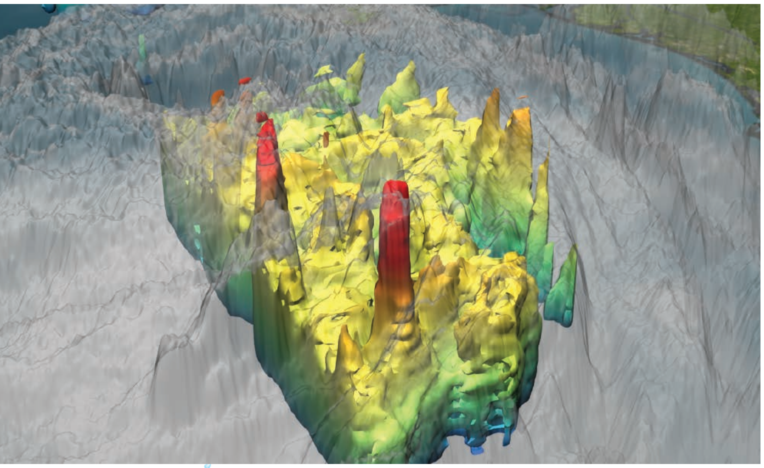


[Left] *Across the contiguous United States, radar systems provide coverage over an average area of 50,000 square miles (~130,000 square kilometers), or out to a range of 125 miles (~200 kilometers) in all directions; however, large gaps between radar sites still exist, especially over the ocean. This map shows the ground-based radar coverage across the United States about 2 miles (~3 kilometers) above the surface.*

ground-based instruments can directly measure or estimate how much precipitation falls to the ground, satellite instruments estimate the amount of electromagnetic radiation (or energy) that is emitted or reflected either from the tops of the clouds or from the rain droplets themselves, providing a top-down view. Spaceborne radar instruments can even observe the three-dimensional structure of precipitation. Such satellite observations are detailed enough to allow scientists to distinguish between rain, snow, and other precipitation types, as well as observe the structure, intensity, and dynamics of storms.

Late 1997 saw the launch of the Tropical Rainfall Measurement Mission (TRMM), a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA). TRMM measured heavy to moderate rainfall over tropical and subtropical regions for over 17 years, until the mission ended in April 2015. Measurements from TRMM advanced our understanding of tropical rainfall, particularly over the ocean, and provided three-dimensional images of storm intensity and structure from space using the first satellite-borne weather radar.

DID YOU KNOW? The design of rain gauges was not consistent until a form of standardization came along in 1677. An English mathematician and astronomer named Richard Townley developed the first rain gauge in England and began making regular measurements of rainfall in January 1677, marking the start of systematic rainfall recording in the British Isles. Nearly all the long-term records of precipitation before this time lacked consistent equipment and practices.

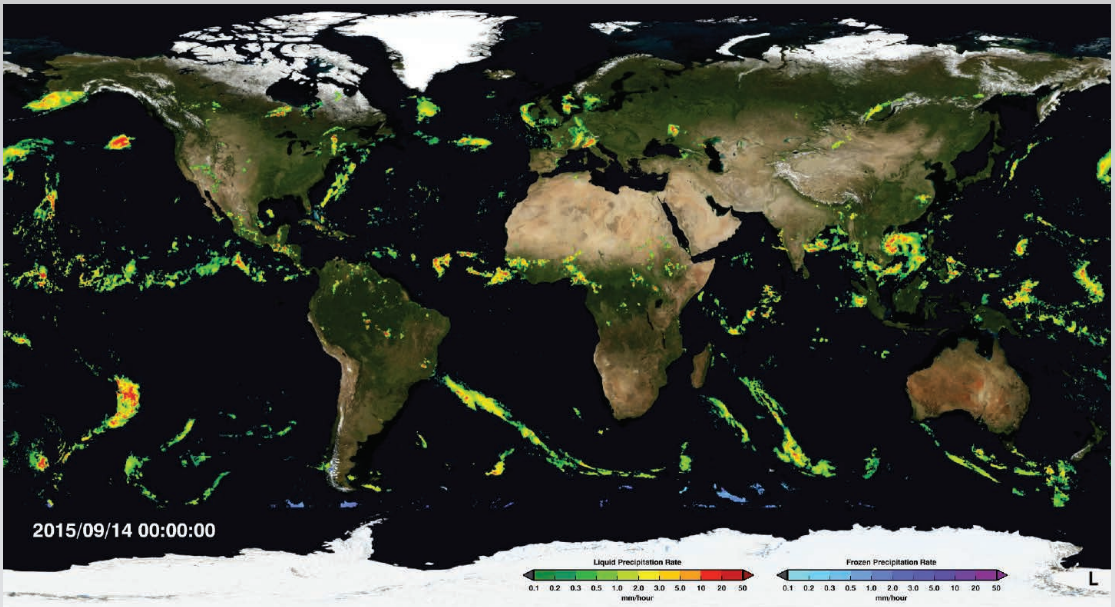


[Left] *TRMM allowed scientists to look inside and under Hurricane Katrina's clouds to see the rain structure on August 28, 2005. Just before Katrina strengthened into a Category 5 hurricane, TRMM observed tall cumulonimbus clouds, depicted as red spikes, emerging from the storm's eyewall and rain bands. The spikes, named hot towers, are associated with tropical cyclone intensification because they release tremendous amounts of heat that fuel the storm. The eyewall hot tower was approximately 10 miles (16 kilometers) tall.*

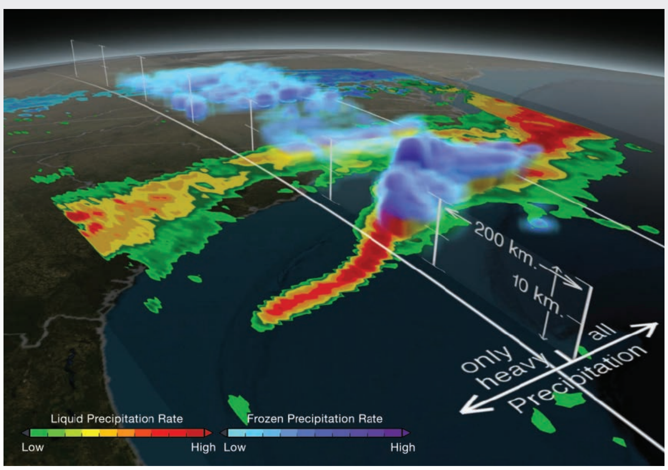
DID YOU KNOW? Not all raindrops are created equal. The size of the falling raindrops depends on several factors, including the cloud type, where the cloud producing the drops is located on the globe, and where the drops originate in the cloud. For the first time, scientists have three-dimensional snapshots of raindrops and snowflakes around the world from space—thanks to the GPM mission.

TRMM's successor is another joint NASA-JAXA mission called the Global Precipitation Measurement (GPM) Core Observatory, launched on February 28, 2014 from the Tanegashima Space Center, in Japan. The Core Observatory carries two instruments—the Dual-frequency Precipitation Radar (DPR) and GPM Microwave Imager (GMI)—collecting observations that allow scientists to dissect storms. Like a diagnostic CAT scan, the DPR provides a three-dimensional profile that shows the intensities of liquid and solid precipitation. The GMI provides a two-dimensional view to look in depth at light rain to heavy rain and falling snow—like an X-ray. The Core Observatory is part of an international constellation of domestic and international satellites that together provide global observations of precipitation from space—called the GPM mission. Together, the constellation observes rain, snow, and other precipitation data worldwide every three hours.

GPM Core Observatory

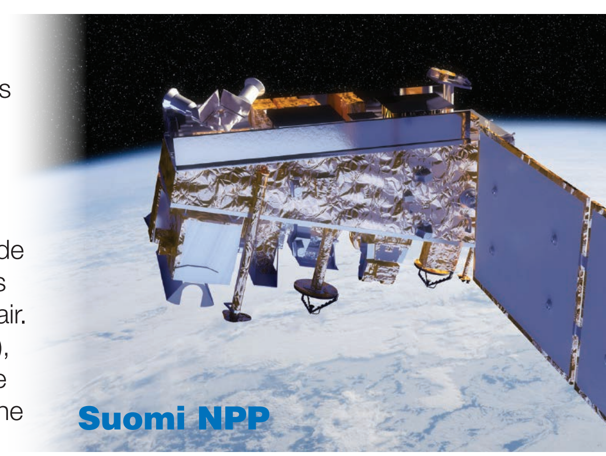


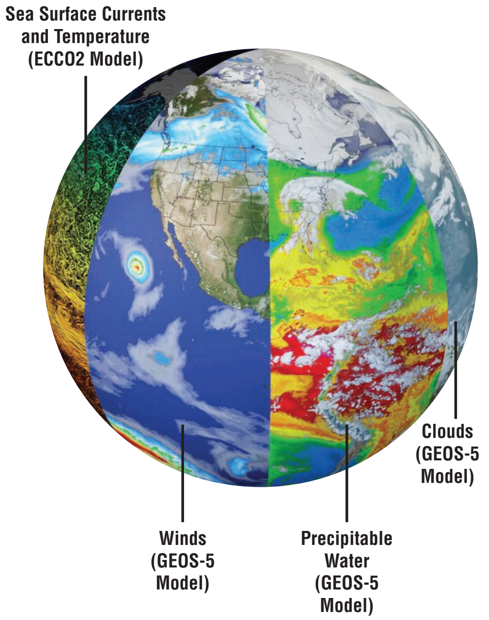
[Above] *This map shows rain and snow across the globe from NASA's Integrated Multi-satellitE Retrievals for GPM data product, called IMERG. This product combines data from the constellation of GPM satellites into a single, seamless map that is updated every half hour, allowing scientists to see how storms move around nearly the entire planet.*



[Left] *This image combines data from the GPM Core Observatory's DPR and GMI and shows the southern extent of a rare late-season snowstorm off the coast of South Carolina on March 17, 2014. Blue shades indicate frozen precipitation, while red to green shades indicate liquid precipitation. Inside the storm over the Atlantic Ocean, precipitation was frozen at high altitudes (blue and purple shades) in the cloud before melting into rain near the surface. Inland, the temperatures were below freezing all the way down to the surface, allowing the formation of shallow, low-level clouds capable of producing snow.*

Other United States (as well as international) satellites provide additional information about the environment that can be used to increase our understanding of Earth's atmosphere and precipitation. For example, NASA's CloudSat mission (launched in April 2006) collects radar observations of clouds, providing information on cloud structure and light precipitation. The joint NASA/National Oceanic and Atmospheric Administration (NOAA) Suomi National Polar-orbiting Partnership (Suomi NPP) satellite (launched in October 2011) and NASA's Aqua satellite (launched in May 2002) also provide precipitation estimates, such as the intensity of precipitation reaching Earth's surface and the amount of precipitation contained within a given column of air. Furthermore, the Geostationary Operational Environmental Satellites (GOES), built by NASA and operated by NOAA, observe clouds in infrared and visible wavelengths, allowing scientists and weather forecasters to routinely track the movement of storm systems and how they change over time.





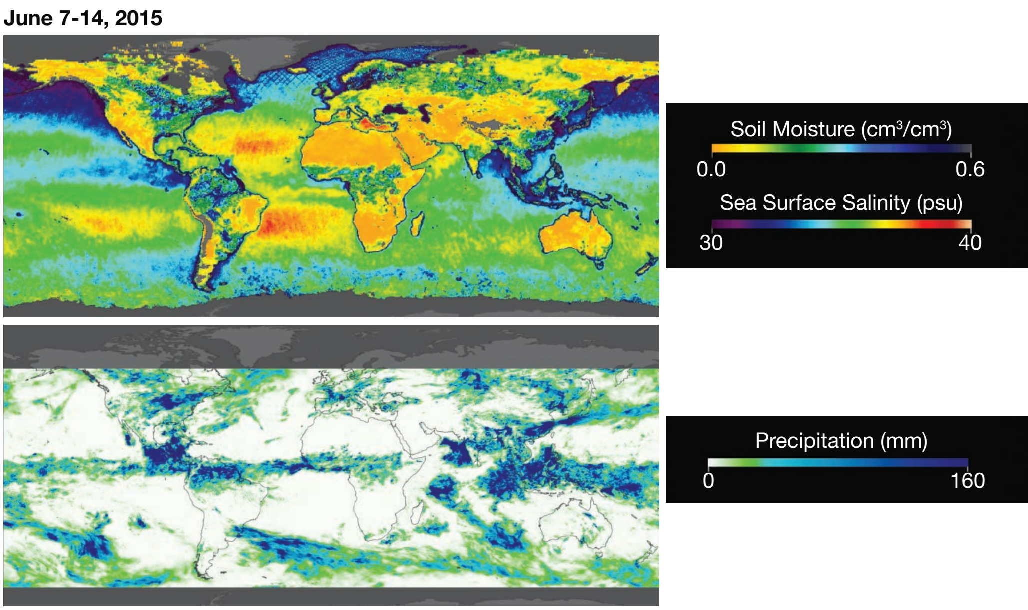
[Above] *While scientists learn a great deal from studying individual Earth components, improved observational and computational modeling capabilities increasingly allow them to study the interactions between these interrelated environmental parameters, leading to unprecedented insight into how the Earth system works—and how it might change in the future.*

Combining Earth Observations to Gain a Global Perspective

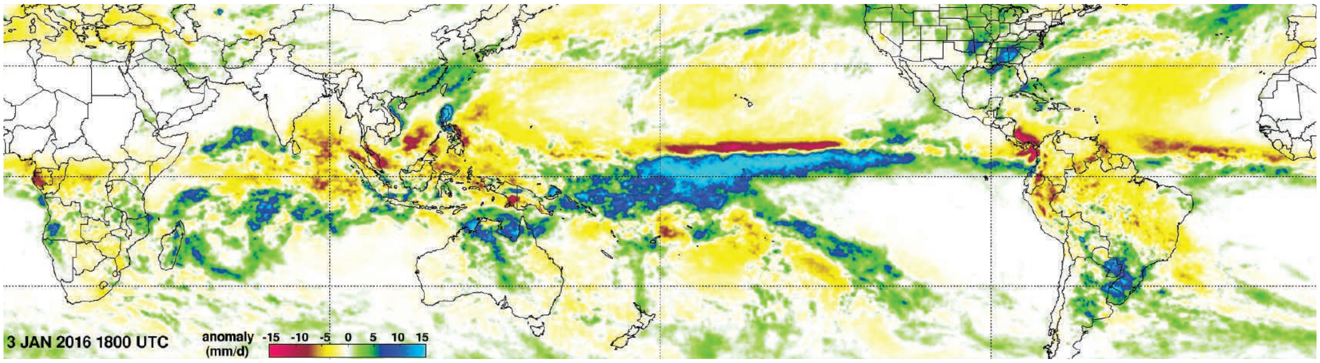
Like parts of the human body, Earth's "spheres" (e.g., atmosphere, hydrosphere, and biosphere) interact with one another in complex ways. For example, Earth's weather and climate systems are fundamentally linked and impacted by interactions with the ocean and land.

To understand Earth as an integrated system, NASA collaborates with its domestic and international partners to support satellite missions and field campaigns that measure various environmental parameters on a variety of spatial and temporal scales. These observational data, coupled with numerical computer models, increasingly allow scientists to better comprehend interactions between Earth's components, or "spheres," and more accurately model weather and climate scenarios such as extreme weather events (e.g., hurricanes) and El Niño.

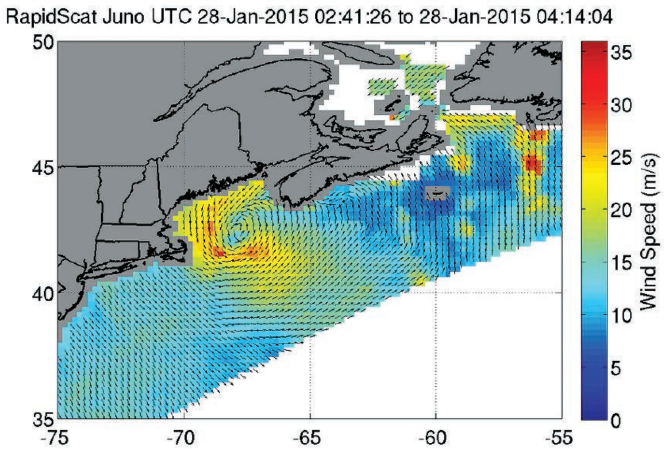
For example, to study hurricanes, scientists use data from a suite of instruments that orbit Earth on several spacecraft to collect information about different aspects of the storm, such as sea surface temperature, humidity, rainfall rates, cloud heights, and surface wind speed. Observing these contributing factors helps scientists to better understand the processes involved in storm formation, movement, and intensification. Furthermore, scientists can ingest datasets such as these into computer models that allow operational forecasters to better predict where, when, and how strong a hurricane may become.



[Right] *This image compares weekly soil moisture and sea surface salinity data (over land and water, respectively) from NASA's Soil Moisture Active Passive (SMAP) mission [top map] with precipitation data from GPM's IMERG [bottom map], from June 7 to June 14, 2015. These maps help reveal how precipitation amounts influence soil moisture conditions and sea surface salinity.*



[Above] *This map reveals where rainfall amounts were above (blue shades) or below (red shades) average, or "normal," conditions during the 2015-16 El Niño. Since day-to-day rainfall is highly variable, the 30-day average that ends on January 3, 2016 is shown. The data were computed from the international constellation of precipitation-relevant satellites, numbering about 10 during this time.*



[Left] *On January 28, 2015, the International Space Station Rapid Scatterometer (ISS-RapidScat) observed the surface winds in a Nor'easter weather system offshore from eastern Cape Cod, Massachusetts with sustained winds between 25 to 30 miles per second (56 and 67 miles per hour/90 to 108 kilometers per hour). Such observations can be combined with other environmental data (such as precipitation data) to help predict the strength and path of storms.*

The ability to observe global precipitation also enables scientists to better understand large-scale climate phenomena such as the El Niño-Southern Oscillation (ENSO) cycle. The ENSO cycle describes the fluctuations in ocean temperature in the equatorial eastern Pacific Ocean. The two modes of this oscillation, El Niño and La Niña, impact global weather patterns and can bring severe drought conditions or intense rainfall events to different parts of the world. While the overall global total rainfall changes very little, global observations of precipitation can show how precipitation is redistributed to specific areas.

Future Earth-observing satellite missions, such as the Cyclone Global Navigation Satellite System (CYGNSS) and the Surface Water and Ocean Topography (SWOT) mission, are scheduled to launch in the coming years. CYGNSS will collect the first frequent space-based measurements of surface wind speeds in the inner core of tropical cyclones to better understand their rapid intensification. The SWOT mission will contribute to a better understanding of the world's ocean and terrestrial surface waters. These and other missions will ultimately enable new data products to aid our understanding of the atmosphere, land, and ocean and their roles in Earth's changing climate for many years to come.

Image credit: Lockheed Martin

[Above] *An artist's concept of the Geostationary Operational Environmental Satellite-R (GOES-R) spacecraft. The GOES-R Series—a collaborative program between NASA and NOAA—is the next generation of United States geostationary weather satellites.*

Photo credit: Jon Shave

Using Precipitation Data in the Real World

Humans are directly impacted by changes in precipitation on a range of scales. For example, an increase in rainfall can cause flooding and/or landslides that affect individual homes, cities, or even entire countries. Flood disasters and torrential rainfall can also have negative health impacts, such as increasing the spread of diseases like malaria. Drought conditions can impact a region's susceptibility to wildfire or diminish crop yields for local farmers—both of which can have cascading effects on the local to regional economy. Access to accurate estimates of precipitation can improve our understanding of growing seasons or indicate where international aid agencies should deliver aid. Among other uses, precipitation and other Earth-observing datasets from NASA are used for forecasting tropical cyclones; monitoring soil moisture conditions and freshwater availability; and predicting flood and drought conditions, landslides, crop yields, and water-related illnesses.

MONITORING AND PREDICTING FLOODS

Photo credit: Brett Davies

Characterizing the surface and weather conditions that can lead to flooding is often difficult due to a lack of ground-based information available to monitor or forecast flood events (particularly in developing countries). To fill some of these data gaps, scientists and forecasters often rely on satellite sources as inputs to hydrologic models that can predict where the water will likely flow once it hits the ground. While the majority of flood models currently focus on local or regional scales (taking into account one drainage basin or watershed) some recent research has shifted to estimating areas of potential flooding on a global scale. For example, the Global Flood Monitoring System (GFMS) is a NASA-funded experimental system that uses real-time satellite precipitation data as part of their flood monitoring and prediction tools. The model combines the satellite precipitation data with a hydrologic model, which includes information about the types of soil, soil moisture, vegetation, slopes, rivers, and streams as well as other factors that affect whether an area will flood. The end product is a series of estimates describing potential flooding conditions that are produced every three hours for the duration of the flood. The GFMS and other regional and global flood modeling networks are important to the scientific research community, reinsurance groups, and humanitarian organizations like the International Red Cross and the U.N. World Food Programme.

DID YOU KNOW? There is about one major flood a day somewhere in the world. These extreme events account for 39% of all natural disaster events and are responsible for 23% of disaster losses.

DID YOU KNOW? Landslides are one of the most pervasive hazards in the world, resulting in more fatalities and economic damage than is generally recognized. They cause thousands of fatalities each year and can cause widespread economic damage from destroying infrastructure and blocking roads. Landslides can occur when saturated soils on vulnerable slopes combine with intense or prolonged rainfall (among other triggers such as earthquakes and human activities). Satellite data can be used to approximate the conditions contributing to landslides over broad areas, such as slope, vegetation, soil moisture, and rainfall.

FORECASTING DISEASE OUTBREAK

Malaria outbreaks after the 2010 floods in Pakistan; E. coli and coliform outbreaks from raw sewage in Mississippi flood waters; and cholera spread by heavy rains in Cameroon, West Africa are among the many health hazards associated with flood disasters and torrential rains. In developing regions with limited or vulnerable clean water infrastructure and health resources, any improvements that increase the lead time for warning systems can make a huge difference in protecting the public. Using satellite data to forecast disease outbreaks is an emerging field. NASA's Malaria Modeling and Surveillance (MMS) Project's Global Situational Awareness Tool (GSAT) combines datasets from a number of satellites, including precipitation estimates, to evaluate the risk of malaria worldwide. GPM's near-global coverage and high-frequency observations also help locate areas at risk for public health crises caused by short-term events such as hurricane-induced flooding, which can cause sewage and sewage-related health issues.

Photo credit: Penn State Center for Infectious Disease Dynamics

IMPROVING AGRICULTURAL CROP FORECASTING

Remotely sensed precipitation estimates play a key role in monitoring and modeling efforts for organizations that track food and water security, like the Famine Early Warning Systems Network (FEWS NET). In addition to the amount and distribution of seasonal rainfall, the timing of the onset of rainfall is an important variable for early estimation of growing season outcomes like crop yield. With their global coverage, satellites can also observe the results of natural disasters such as short- and long-term droughts, floods, and persistent or deficient snow cover that can each affect agricultural productivity. Satellite precipitation estimates from GPM, combined with other environmental datasets, are used to determine the extent and availability of surface rainfall over farm and ranch land within the U.S. Air Force Weather Agency's AGRicultural METeorology (AGRMET) model. AGRMET analyzes and forecasts rain and snow estimates to use within hydrologic models. Data from NASA's Soil Moisture Active Passive (SMAP) mission (and other satellite sensors) can provide additional information on how much water is in the soil, which is useful for assessing drought and flood conditions, and estimating groundwater supplies.

Photo credit: United Soybean Board

Improving Precipitation Estimates through Field Campaigns

NASA conducts *field campaigns*—observational studies planned for specific locations over a defined time period—from a variety of platforms (i.e., aircraft and ground-based stations) to further science and advance the use of satellite precipitation data. Data from these and future field campaigns are used to improve precipitation estimates from NASA's suite of precipitation measurement missions.

OLYMPIC MOUNTAINS EXPERIMENT (OLYMPEX)

November 2015 – February 2016

[Right] *Heavy rain caused flooding at the Doppler on Wheels (DOW) radar site around Lake Quinault, Washington.*

Photo credit: Josh Wurman/Center for Severe Weather Research

HURRICANE AND SEVERE STORM SENTINEL (HS3)

2012 – 2014 Atlantic Hurricane Seasons

[Right] *Flight path for unmanned Global Hawk during an HS3 investigation.*

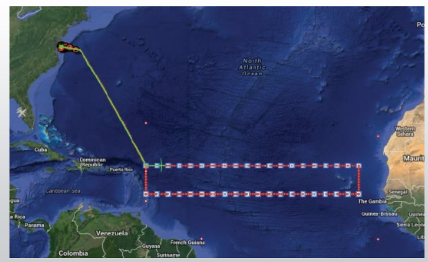


Photo credit: NASA

INTEGRATED PRECIPITATION AND HYDROLOGY EXPERIMENT (IPHEx)

May 1 – June 15, 2014

[Right] *NASA's Dual-frequency Dual-polarized Doppler Radar before heading to North Carolina.*

Photo credit: NASA

IOWA FLOOD STUDIES (IFloodS)

May 1 – June 15, 2013

[Right] *Instrumentation in eastern Iowa for the IFloodS campaign.*

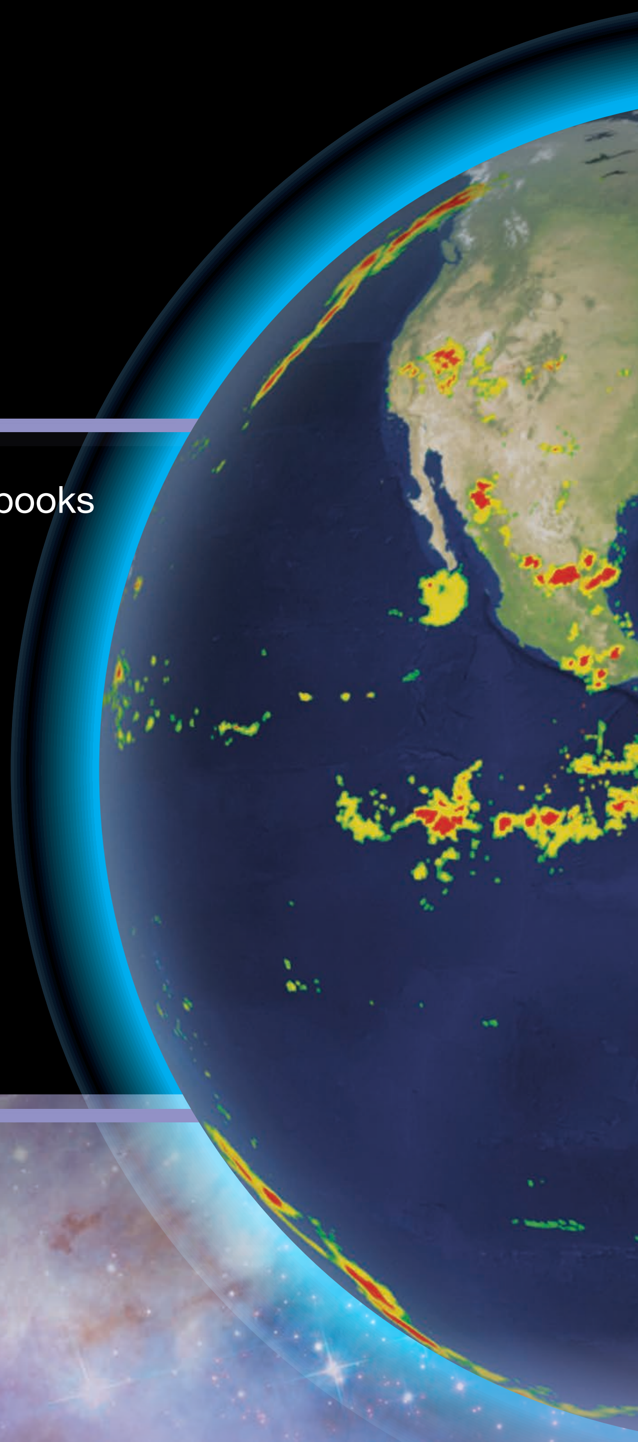
Photo credit: Aneta Goska/Iowa Flood Center

GLOBAL PRECIPITATION MEASUREMENT COLD-SEASON PRECIPITATION EXPERIMENT (GCPEx)

January 17 – February 29, 2012

[Right] *Heavily instrumented ground site located in Ontario, Canada.*

Photo credit: Gail Skofronick-Jackson/NASA



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