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Review of NASA Earth Observations, Recent Science, and Practical Applications

Stephanie Schollaert Uz and Assaf Anyamba

Abstract

Freely available government satellite observations enable scientists to monitor changes across the Earth system. Calibrated and validated global satellite data have advanced our understanding of interactions within and between the energy, carbon, and water cycles. In addition to answering fundamental science questions, these environmental indicators are also used to inform practical decisions relevant to agriculture, health, renewable energy, infrastructure, and more. Assimilating satellite observations into models fills data gaps and provides predictive tools. Partnering with other organizations to reach new communities and combining environmental data with sector-specific data increases its utility and societal benefit. Additionally, under the principles of open science, government agencies are working together to make useful information derived from global observations, both data and software tools, more easily accessible. This paper reviews recent NASA Earth satellite missions, highlights a few examples of science discoveries and practical applications, and describes new activities and directions.

Introduction

The National Aeronautics and Space Administration (NASA) satellite fleet (Figure 1) observes Earth systems from space—over land and ocean from gases at the top of the atmosphere to groundwater changes below the surface—to increase understanding of planetary processes. Data collected from the Earth observing fleet enables monitoring and analysis of variables such as temperature, sea level, polar ice extent, vegetation on land and in the ocean, precipitation, soil moisture, groundwater, human nightlights, and more. Change over time is measured through well-calibrated high quality data records that are assimilated into models to analyze historical trends, predict weather and climate patterns from days to seasons, and project future patterns over the next century. NASA partners with other organizations to make the data more broadly useful and actionable to sectors such as food security, health, disaster response, and building climate resilience at the local level. Through open science principles, these data and methods are freely available to enable scaling and broader use by other entities, including academic, government, and the private sector.

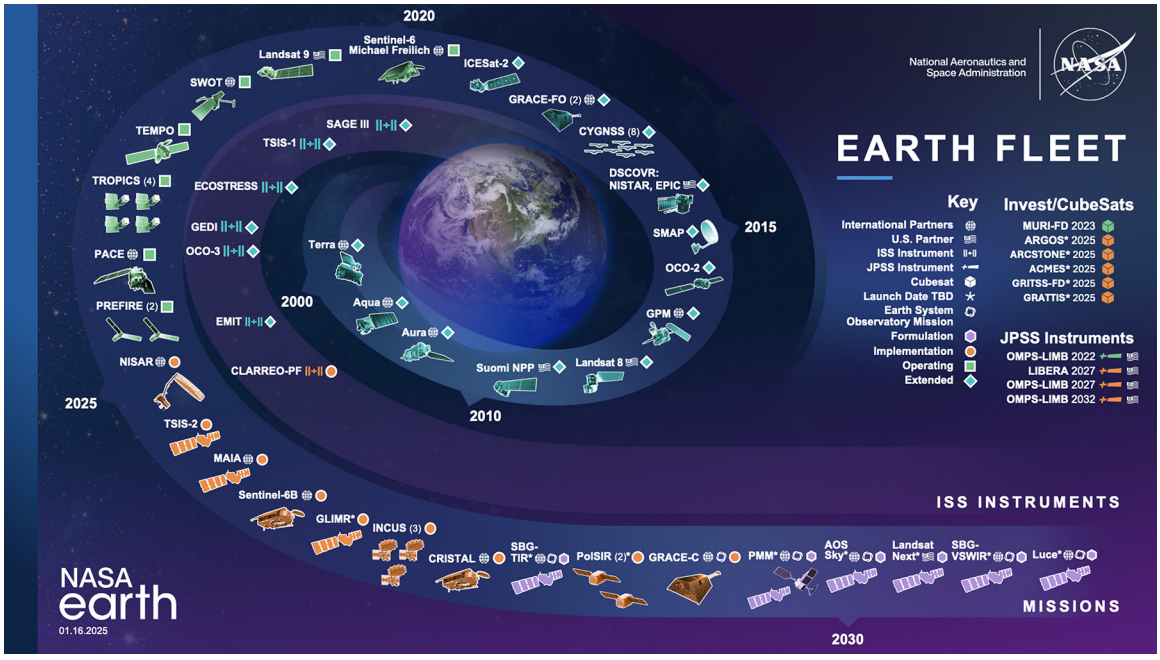


Figure 1. NASA Earth observing fleet as of January 2025 with missions color-coded by phase and arranged chronologically from earliest launch in the center outward with a teal diamond for extended operation, a green square for operating, an orange circle for implementation, and a purple hexagon for preformulation missions planned for future launch. Instruments operating on the International Space Station (ISS) are similarly displayed on the inner swirl. Source: https://svs.gsfc.nasa.gov/30065.

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Observing Change

NASA Earth observations advance and extend research and applications for the benefit of society. The science and products from NASA missions are vast and diverse; thus, we share only a few examples here. The earliest and longest serving is the sustained land imaging program, jointly operated by NASA and the U.S. Geological Survey, whose series of Landsat satellites since 1972 pioneered and progressively advances technology with the addition of thermal sensing to its optical imaging since 1982. Landsat imagery is routinely used to observe changes in land cover and land use, fires, floods, glaciers, ice sheets, vegetation stress, urban heat, water quality, bathymetry, and more. Freely available since 2008 (Landsat Science 2023), the direct and indirect use of Landsat data led to and economic value of $25.6 billion in 2023 alone (Loomis *et al.* 2024). Now in development, LandsatNext, with launch planned around 2030, will include more spectral bands on its instruments, with finer spatial resolution at 10 to 20 m for visible bands (Figure 2) with an anticipated leap in economic value to societal applications from its imagery and projects (LandsatNext 2025).

The newest addition to the NASA satellite fleet is the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission in orbit since February 2024, extending and advancing the global ocean color record, pioneered and stewarded by NASA Goddard Space Flight Center for over 30 years (McClain *et al.* 2022). Its Ocean Color Instrument hyperspectral spectrometer enables the development of proxies for phytoplankton identification beyond the main pigment observed in the historical record, chlorophyll a, to more pigments that can be used to discriminate phytoplankton community structure (Werdell *et al.* 2019; McKibben *et al.* 2024). This is important for understanding changes at the base of the marine food web, both as a source for food that sustains fisheries and as the critical role of the ocean carbon sink in buffering Earth's climate system (Schollaert Uz *et al.* 2019), both of which will be further enhanced in coastal regions by upcoming spectroscopy missions: Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR) in geosynchronous orbit with a view that includes the waters of the U.S. gulf coast, the east and west coasts, Hawaii, and the Amazon River plume; and the polar-orbiting higher spatial resolution global Surface Biology and Geology mission (Dierssen *et al.* 2023).

Surface temperature measurements from space, both land and ocean, are essential for monitoring heat transfer between land, ocean, cryosphere, and atmosphere. Heat and moisture exchange are a main driver of global weather patterns. Surface temperature drives processes at the land surface; e.g. the difference between the land surface and air temperatures results in energy exchange within the planetary boundary layer. Changes in land temperature influence air temperature and dynamics, inducing convection within the boundary layer, surface winds, cloudiness, and precipitation. Surface temperatures have been derived from measurements taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites for over 24 years and from various Landsat sensors since 1982. Such long-term records are critical in understanding temperature variability and trends on the Earth's surface. Similarly, sea surface temperature is a key variable for monitoring ocean processes, that drive energy exchange across the air–sea interface and transfer heat from the tropics poleward through ocean currents (NASA–Physical Oceanography Distributed Active Archive Center 2025).

Since 1992, satellite-borne altimetry has been used to derive water level measurements, including sea-surface height, as well as water levels in rivers, lakes, and reservoirs. The satellite altimetry record shows that global mean sea level has been rising around 3.3 mm/yr since 1993, and that rate is accelerating (Nerem *et al.* 2018; Hamlington *et al.* 2020). The NASA sea level change website (sealevel.nasa.gov) shares updated statistics on global sea level including contributions from thermal expansion, melting glaciers, and Greenland and Antarctica ice mass changes. The 2022 launch of the Surface Water Ocean Topography (SWOT) mission provides finer spatial resolution to better detect ocean features associated with mesoscale processes—and, for the first time, global submesoscale processes (1 to 100 km)—as well as river reach and water levels on land, from which hydrologic fluxes can be calculated (NASA EarthData 2024; Archer *et al.* 2025).

Decades of stable, well-validated Earth observations contribute to the body of knowledge about interannual patterns such as the El Niño Southern Oscillation (ENSO), as well as long-term trends. ENSO is an interannual change in ocean-atmosphere dynamics observed in the eastward movement of warm sea-surface temperatures along the equator in the Pacific Ocean (Philander 1992; McPhaden 1999). However, its influence is not limited to the equatorial region and has been linked to variability in weather patterns around the world, including extreme temperatures, rainfall, and drought. The changing dynamics have also been shown to affect primary production at the base of the marine food web through changes in upper-ocean temperature and stratification, which control the availability of nutrients (nitrogen, phosphate, iron) necessary for phytoplankton growth (Feldman *et al.* 1984; Behrenfeld *et al.* 2006; Schollaert Uz *et al.* 2017). The link between physical forcing and biological response is now evident from space at a finer scale than ever before possible with SWOT sea-surface heights revealing eddies and currents that entrain nutrients into the sunlit euphotic zone, where they fuel phytoplankton blooms that PACE hyperspectral data can detect. In an example collocated over the western Atlantic in 2024

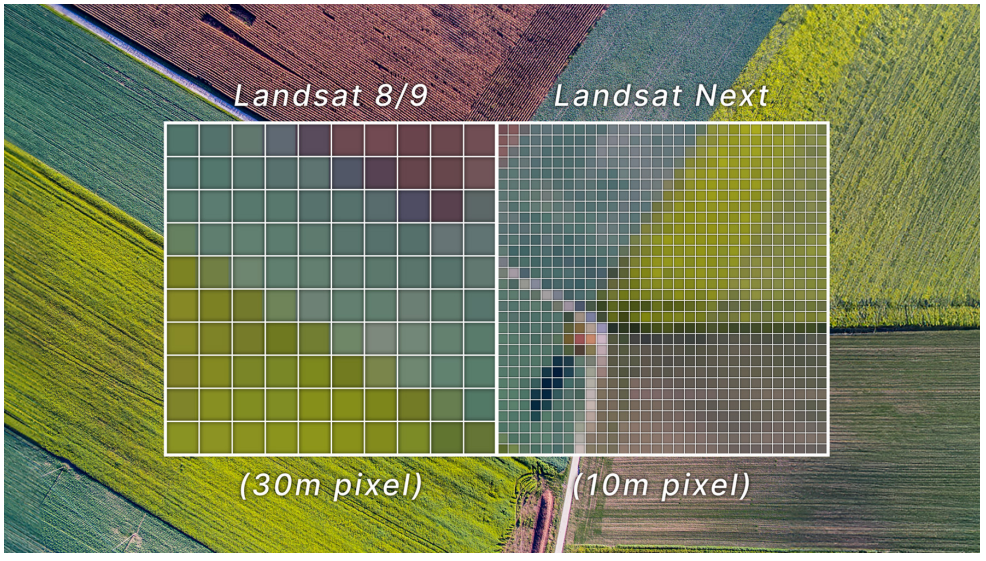


Figure 2. Landsat 8/9 currently observe visible wavelengths at 30-m spatial resolution, while Landsat Next is being designed to observe the visible at 10- to 20-m spatial resolution, with the difference between 30- and 10-m resolution shown here for agricultural fields. Source: https://landsat.gsfc.nasa.gov/satellites/landsat-next/.

(Figure 3), physical features coincide with varying concentrations of open ocean small phytoplankton communities, detected by the method of Lange *et al.* (2020).

Global NASA Earth observation data are publicly available, with the data catalog currently being consolidated in 2025 along with tools for visualization and analysis on https://www.earthdata.nasa.gov/. Examples discussed here and below are summarized in Table 1, including the main characteristics and links to data.

Additionally, assimilating satellite data into models along with the observational record collected on land, at sea, and in the air provides complete historical reanalyses, future forecasts from days to seasons, and longer-term decadal-scale projections. For example, the NASA Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) annual world-wide average temperature time series shows the past 10 years as the warmest since recordkeeping began in 1880 (Figure 4). The globally averaged temperature in 2024 was 2.30°F (1.28°C) above the agency's 20th-century baseline (1951 to 1980), topping the record set in 2023 (NASA, 2025). The new record comes after 15 consecutive months of monthly temperature records between June 2023 through August 2024—an unprecedented heat streak.

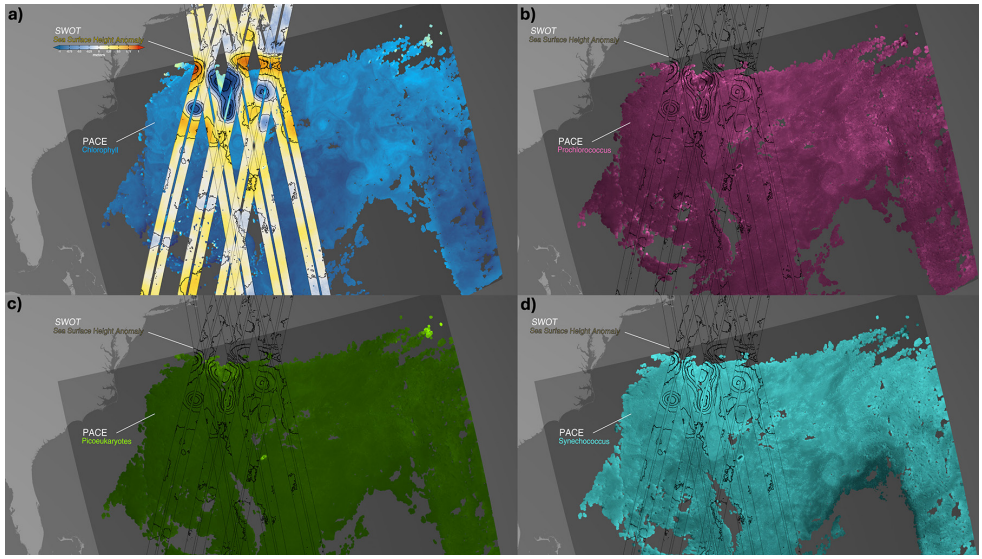


Figure 3. Northwest Atlantic Surface Water Ocean Topography (SWOT) sea-surface height anomalies on 8 Aug 2024 shown in height contours coincident with Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) hyperspectral measurements used to discriminate concentrations of the phytoplankton pigment chlorophyll (blue) and picophytoplankton communities (a); Prochlorococcus (magenta) (b); picoeukaryotes (green) (c); and Synechococcus (teal) (d). Source: NASA Scientific Visualization Studio, https://svs.gsfc.nasa.gov/5432/.

Table 1. Listing of satellite data products, characteristics and sources referenced as examples here. Note that the list in the table represents only a partial listing of NASA Earth science data products.

Dataset	Spatial resolution	Period	Frequency	Indicator	Link/DOI
MODIS-Aqua & Terra	1km	2000-present *deorbit ~2026*	1-2 day revisit	Surface temperature, vegetation, land cover	10.5067/MODIS/MYD11A1.061
Landsat 8&9	30m	2013-present	16-day revisit per satellite or 8-day combined	Surface temperature, vegetation, land cover	10.5066/P960F8OC
NLCD from Landsat	30m	2001-2023	Annual	Land cover classification	10.5066/P94UXNTS
PACE OCI	1km	2024-present	1-2 day revisit	Aquatic & land vegetation, air & water quality, clouds	https://www.earthdata.nasa.gov/data/instruments/oci
SWOT	1km	2023-present	21-day revisit	Altimetry, sea-surface height, river reach	https://podaac.jpl.nasa.gov/SWOT
FIRMS	30m, 1km	2000-present	Near-real-time daily, weekly+	US/Canada, Global fires	https://www.earthdata.nasa.gov/data/tools/firms
LANCE	250m, 1km	2000-present	Near-real-time daily, weekly+	Floods, sea ice, and other products	https://www.earthdata.nasa.gov/data/projects/lance
Black Marble	30m, 500m	2012-present	Daily, monthly+	Human activity from night lights	https://blackmarble.gsfc.nasa.gov

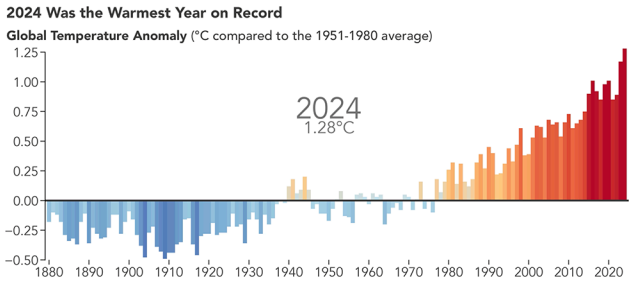


Figure 4. Surface temperature anomalies compared to the 1951 to 1980 baseline averaged over the globe from land and ocean data. Data source: https://data.giss.nasa.gov/gistemp/. Image Source: NASA Earth Observatory Image of the Day for January 11, 2025, https://earthobservatory.nasa.gov/images/153806/2024-was-the-warmest-year-on-record.

Increasing Practical Use through Partnerships

Applying the best-available science to inform decisions has been the objective of the NASA Applied Sciences program that has been integrated into the Earth Science Division Earth Science to Action strategy for the next decade (NASA 2024). The goal is to bridge cutting-edge research with applications that respond to end-user needs, often through partnership with practitioners who can benefit from the new information. The earliest cooperative interagency effort to apply NASA satellite data for agricultural monitoring, assessment, and forecasting began with the Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) program in 1980 by NASA, the U.S. Department of Agriculture (USDA), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of the Interior, and the U.S. Agency for International Development (USAID) (NASA-TM-84202 1981). The goal of AgRISTARS was to determine the feasibility of integrating aerospace remote sensing technology into USDA data acquisition systems. After the concept was proven, mainly using Landsat satellite data, the simultaneous availability of coarser but higher temporal resolution Normalized Difference Vegetation Index (NDVI) data from the Advanced Very High Resolution Radiometer instrument meant that global agricultural vegetation conditions could be monitored and assessed on weekly to seasonal time scales to estimate crop production (Tucker 1979; Tucker *et al.* 1980; Hatfield 1983).

Since then, NASA routinely provides satellite data to the USDA Foreign Agricultural Service (FAS) International Production Assessment Division Crop Explorer Application (https://ipad.fas.usda.gov/cropexplorer/). The primary mission of the International Production Assessment Division is to produce the most objective and accurate assessment of global agricultural production and the conditions affecting food security around the world through monthly production estimates of agricultural commodities, i.e. corn, barley, rice, wheat, soybean (U.S. Department of Agriculture 2025). This system has been supplemented with NDVI data since 2005 from both Terra and Aqua MODIS instruments (Becker-Reshef *et al.* 2010). The system operates under the Global Agricultural Monitoring (GLAM) (https://glam1.gsfc.nasa.gov/) currently ingesting additional data sets from the Visible Infrared Imaging Radiometer Suite onboard the Suomi National Polar-Orbiting Partnership spacecraft and Sentinel-2 from the European Space Agency. Data from the system are also utilized by the USDA National Agricultural Statistics Service for domestic crop yield estimates (Johnson *et al.* 2021) and by various agri-businesses nationally and internationally. A similar interagency program led by USAID through the Famine Early Warning Systems Network (https://fews.net/) started operating in 1985. Temperature is combined with NDVI for estimating crop water demands and drought severity assessments (Karnieli *et al.* 2010). These data are used to evaluate anomalies in crop growth and predict environmental affects crop yield and production across different regions around the world to plan and prepare humanitarian response (Anyamba *et al.* 2014; Glennie and Anyamba 2018).

Water supply for irrigation is critical to agriculture. Thus, the USDA FAS International Production Assessment Division utilizes NASA global water measurements derived from various multi-agency satellite radar altimeters including the new SWOT altimeter, as well as the NASA Ice, Cloud, land Elevation Satellite-2 (ICESat-2) laser altimeter (https://ipad.fas.usda.gov/cropexplorer/global_reservoir/). This archive and near real time surface level measurements are used as a proxy for the volume of water stored in lakes and reservoirs, reflecting the potential irrigation and crop yield for the surrounding basin (Birkett *et al.* 2022). NASA also provides soil moisture measurements to USDA and others to optimize water resource management for agriculture and provide earlier warning of future crop stress (Das *et al.* 2018; Liu *et al.* 2020).

In addition to agriculture, water levels and precipitation are relevant for hydroelectric power. Water levels are currently being explored for addition to the NASA Prediction Of Worldwide Energy Resources (POWER) project, which provides solar radiation and meteorological data in support of renewable energy, building energy efficiency, and agroclimatology (https://power.larc.nasa.gov). Current routine data within this project include energy fluxes from NASA's Global Energy and Water Cycle Exchanges (GEWEX) and Clouds and the Earth's Radiant Energy System (CERES), precipitation from the multi-agency Global Precipitation Measurement (GPM) mission's Integrated Multi-satellite Retrievals for GPM (IMERG), and meteorological fields from the Modern Era Retrospective Analysis for Research and Applications (MERRA-2), and Goddard Earth Observing data assimilation System (GEOS) near-real time forecasts (Bloom *et al.* 2005; Su *et al.* 2007; Rienecker *et al.* 2008, 2011; Stackhouse *et al.* 2011; Huffman *et al.* 2014; Bosilovich *et al.* 2016).

A natural or human-caused disaster often results in loss of infrastructure and communications, making remote sensing a vital resource for assessing damage and providing aid. The Federal Emergency Management Agency (FEMA) often requests near-real-time information from NASA during a disaster to help identify dynamic events such as flood extent, e.g. caused by a hurricane, to inform emergency response. Satellite-derived data of nighttime lights, the NASA Black Marble product, are another tool for monitoring human systems, including settlements, energy infrastructure, power outages, fishing activity, fires, gas flares, disaster effects, and recovery (Román *et al.* 2018). The NASA Fire Information for Resource Management System (FIRMS) was created through partnership with the U.S. Forest Service to provide active near-real-time mapping of fires and hotspots in the United States, Canada, and globally derived from several satellites and provided through a variety of data formats, e.g. shapefiles, and even text files. NASA Land, Atmosphere Near real-time Capability for Earth observation (LANCE) supports users interested in monitoring a variety of natural and human-caused events using near-real-time data provided faster than routine processing allows, i.e. within 3 hours of satellite acquisition. In addition to fires, LANCE provides near-real-time data on air quality, volcanic ash plumes, smoke plumes, floods, ice extent, and vegetation.

A partnership with the Centers for Disease and Prevention (CDC) Environmental Public Health tracking network was established to reach new audiences within the health sector (Amos *et al.* 2023). Health sector researchers or professionals may not be staffed or equipped to work with large, global environmental data and models; thus, getting NASA products into the existing CDC Environmental Public Health Tracking portal provides the benefit of easier access to maps of air quality, floods, and other environmental features (https://ephtracking.cdc.gov/DataExplorer/). Also, the CDC environmental public health tracker tool includes health data sets, which can now be analyzed side-by-side with NASA products to study environmental health effects, e.g. wildfire smoke distribution and emergency department visits for asthma.

Vector-borne disease outbreaks are influenced by weather patterns that can be observed and predicted through the application of satellite-derived variables and models. Conditions conducive to mosquito-borne pathogens are observed through temperature, precipitation, soil moisture, vegetation, and land cover. Satellite products are assimilated into habitat suitability models that capture the phenology of disease vectors. For instance, above-normal temperatures influence mosquito survival, the susceptibility of mosquitoes to viruses, mosquito population growth rate, distribution, and seasonality and virus transmission patterns, vector population seasonality (Reisen *et al.* 1993; Gubler *et al.* 2001; Epstein 2005). Increased precipitation can increase mosquito larval habitats or create

new habitats and an overall increase in mosquito vector populations. Conversely, unusually low rainfall or drought can reconfigure habitats by concentrating water into small pools, potentially increasing the proportion of container-breeding mosquito vectors and forcing the disease hosts into human settlements, increasing vector–human contact and resulting in transmission (Figure 5). The USDA Center for Medical, Agricultural, and Veterinary Entomology together with NASA, NOAA, and the Defense Department established the Rift Valley fever (RVF) monitor (Linthicum *et al.* 1999). At global scale, anomalies in precipitation and temperature associated with the ENSO influence outbreaks of several human and animal diseases including RVF, Murray Valley encephalitis, chikungunya, malaria, dengue, and cholera (Anyamba *et al.* 2019).

Over the last 25 years, the use of satellite remote sensing for vector-borne disease early warning has been demonstrated with the NASA Applied Sciences Health and Air Quality Program supporting several partnerships at national, regional and international levels. Satellite-derived climate data are used in designing and building disease risk prediction models that have now been successfully adopted into operational frameworks. The California Vectorborne Disease Surveillance System (https://maps.vectorsurv.org/arbo) issues information to various agencies on the risk of West Nile virus (WNV), dengue and other arbovirus activity (Carney *et al.* 2011). Arbovirus Mapping and Prediction to forecast mosquito-borne disease outbreaks (ArboMAP) (https://ecograph.net/arbomap/) provides early warning of WNV in many regions of the U.S. Northern Great Plains (Wimberly *et al.* 2014). The Vibrio Prediction Hub (https://vibrio-prediction-ufl.hub.arcgis.com/) is a global early warning system for cholera (Jutla *et al.* 2010). There are also efforts to adapt habitat suitability models with climate models, indicating that more extreme rainfall and rising temperatures are likely to increase environmental suitability for vector-borne diseases over the coming decades.

As communities try to build resilience to rising temperatures, extreme rainfall, and other perils, they need data to inform their decisions. Applying NASA global data requires figuring out which large data sets may inform local action and how practitioners could use them. In Prince George's County, Maryland, where NASA Goddard is located, a new project is working directly with the community in an effort to better understand what data could inform their decisions around building resilience and preparedness to extreme weather. Our collaboration started with a heat mapping assessment of temperature from Aqua-MODIS and Landsat layered with local health and socioeconomic information to pinpoint areas where the population is most vulnerable to extreme heat. This research helps Prince George's County prioritize programs that protect residents and workers from heat-related risks to improve the health and safety of the community (Schollaert Uz *et al.* 2025).

To increase the pace and quality of scientific discoveries and benefit from Earth observations, NASA is partnering with other organizations to increase findable, accessible, reproducible open science over the next decade. Specifically, open-source science is a commitment to the open sharing of software, data, and knowledge as early as possible in the scientific process. A related activity seeks to consolidate Earth data and insights from agencies across the federal government, also serving as the gateway to other interagency cooperative efforts such as the U.S. Sea Level Change Portal. Under the Earth Information Center (https://earth.gov), high-priority data such as crop conditions, air quality, energy, and extreme events are shared in an easily accessible format in which someone without special software or coding skills can select an area and plot the distribution of that area's projected number of days above 90°F from 30 ensemble members of climate model projections (Figure 6).

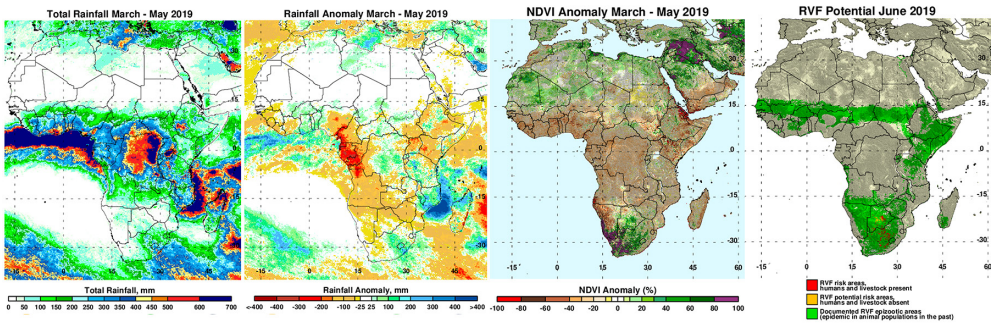


Figure 5. Variables that drive Rift Valley fever (RVF) models include temperature, total rainfall, rainfall anomalies, and Normalized Difference Vegetation Index (NDVI) anomalies, here shown for March to May 2019 preceding June 2019 RVF potential risk, where red areas in central South Africa and Botswana represent isolated risk to humans and livestock and green represents areas of documented past RVF epidemics in livestock. The model uses dynamic variables measured from satellite combined with baseline variables: elevation, human, and livestock density. Source: https://ars.usda.gov/saa/cmave/rvf.

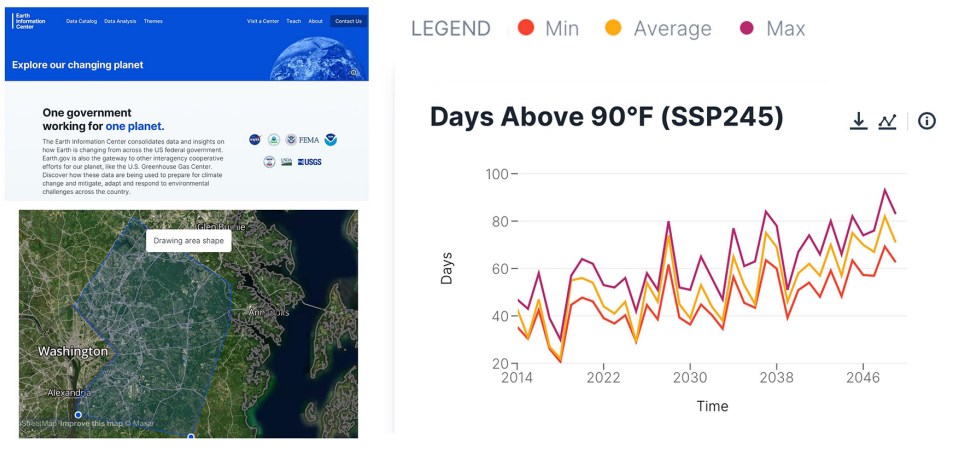


Figure 6. Number of extreme heat days (above 90°F) projected for the mid-range socioeconomic pathway (SSP 245) over the next decades in Prince George's County, MD, near NASA Goddard. Source: NEX-GDDP-CMIP6 retrieved from earth.gov.

Summary

This review highlights some recent progress in research and applications from the perspective of observing Earth from space. These examples do not include all recent advancements from these national assets because there are too many to list here. Several new missions, such as SWOT and PACE, extend long-term satellite records while providing new capabilities to deepen the body of knowledge about how our planet works and how its systems and processes are changing. To take full advantage of this cutting-edge research and development, we also look for opportunities to put the knowledge to use solving practical problems, informing decision makers and policy makers across a variety of sectors from agriculture, renewable energy, disaster response, health, and helping state and local communities to build their resilience and preparedness. Partnerships and open science facilitate the transfer of technology, knowledge, and data products to new users to maximize the utility of these valuable public resources. Efficient delivery by the federal government of reliable expertise and information derived from NASA Earth observations directly benefits individuals, businesses, and local governments, supporting national security and economic prosperity.

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References

Amos, H. M., N. K. Skaff, S. Schollaert Uz, F. S. Policelli, D. Slayback, E. Macorps, J. J. Jo, K. Patel, C. A. Keller, P. Abue, V. Buchard and A. K. Werner. 2023. Public health data applications using the CDC tracking network: Augmenting environmental hazard information with lower-latency NASA data. *GeoHealth* http://doi.org/10.1029/2023GH000971.

Anyamba, A., J. L. Small, S. C. Britch, C. J. Tucker, E. W. Pak, C. A. Reynolds, J. Crutchfield, and K. J. Linthicum. 2014. Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns. *PLoS ONE* 9(3):e92538. https://doi.org/10.1371/journal.pone.0092538

Anyamba, A., J.-P. Chretien, S. C. Britch, R. P. Soebiyanto, J. L. Small, P. Jepsen, B. M. Forshey, J. L. Sanchez, R. D. Smith, R. Harris, C. J. Tucker, W. B. Karesh and K. J. Linthicum. 2019. Global disease outbreaks associated with the 2015-2016 El Niño event. *Nature Scientific Reports* 9:1930. https://doi.org/10.1038/s41598-018-38034-z.

Archer, M., J. Wang, P. Klein, G. Dibarboure and L.-L. Fu. 2025. Wide-swath satellite altimetry unveils global submesoscale ocean dynamics. *Nature* 640:691–696. https://doi.org/10.1038/s41586-025-08722-8.

Becker-Reshef, I., C. Justice, M. Sullivan, E. Vermote, C. Tucker, A. Anyamba, J. Small, E. Pak, E. Masuoka, J. Schmaltz, M. Hansen, K. Pittman, C. Birkett, D. Williams, C. Reynolds and B. Doorn. 2010. Monitoring global croplands with coarse resolution earth observations: The Global Agriculture Monitoring (GLAM) project. *Remote Sensing* 2:1589–1609.

Behrenfeld, M. J., R. T. O'Malley, D. A. Siegel, C. R. McClain, J. L. Sarmiento, G. C. Feldman, A. J. Milligan, P. G. Falkowski, R. M. Letelier and E. S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. *Nature* 444:752–755. https://doi.org/10.1038/nature05317.

Birkett, C. M., K. O'Brien, S. Kinsey, M. Ricko and Y. Li. 2022. Enhancement of a global lake and reservoir database to aid climate studies and resource monitoring utilizing satellite radar altimetry. *Journal of Great Lakes Research* 48:37–51.

Bloom, S., A. da Silva, D. Dee, M. Bosilovich, J.-D. Chern, S. Pawson, S. Schubert, M. Sienkiewicz, I. Stajner, W.-W. Tan and M.-L. Wu. 2005. Documentation and validation of the Goddard Earth Observing System (GEOS) data assimilation system, version 4, Technical Report Series on Global Modeling and Data Assimilation, NASA/TM-2005-104606, Vol. 26.

Bosilovich, M. G., F. R. Robertson, L. Takacs, A. Molod and D. Mocko. 2016. Atmospheric water balance and variability in the MERRA-2 reanalysis. *Journal of Climate* 30:1177–1196. https://doi.org/10.1175/jcli-d-16-0338.1.

Carney, R. M., S. C. Ahearn, A. McConchie, C. Glasner, C. Jean, C. Barker, B. Park, K. Padgett, E. Parker, E. Aquino and V. Kramer. 2011. Early warning system for West Nile virus risk areas, California, USA. *Emerging Infectious Diseases*. 17(8):1445–1454. https://doi.org/10.3201/eid1708.100411.

Das, N. N., D. Entekhabi, R. S. Dunbar, A. Colliander, F. Chen, W. Crow, T. J. Jackson, A. Berg, D. D. Bosch, T. Caldwell, M. H. Cosh, C. H. Collins, E. Lopez-Baeza, M. Moghaddam, T. Rowlandson, P. J. Starks, M. Thibeault, J. P. Walker, X. Wu, P. E. O'Neill, S. Yueh and E. G. Njoku. 2018. The SMAP mission combined active-passive soil moisture product at 9 km and 3 km spatial resolutions. *Remote Sensing of Environment* 211:204–217. https://doi.org/10.1016/j.rse.2018.04.011.

Dierssen, H. M., M. Gierach, L. S. Guild, A. Mannino, J. Salisbury, S. Schollaert Uz, J. Scott, P. A. Townsend, K. Turpie, M. Tzortziou, E. Urquhart, R. Vandermeulen and P. J. Werdell. 2023. Synergies between NASA's Hyperspectral Aquatic Missions PACE, GLIMR and SBG: Opportunities for new science and applications. *JGR Biogeosciences* 128(10):e2023JG007574. https://doi.org/10.1029/2023JG007574.

Epstein, P. R. 2005. Climate change and human health. *New England Journal of Medicine* 353:1433–1436

Feldman, G. C., D. Clark, and D. Halpern. 1984. Satellite color observations of the phytoplankton distribution in the eastern equatorial Pacific during the 1982-1983 El Niño. Science, 226, 1069–1071, https://doi.org/10.1126/science.226.4678.1069

Glennie, E. and A. Anyamba. 2018. Midwest agriculture and ENSO: A comparison of AVHRR NDVI3g data and crop yields in the United States Corn Belt from 1982 to 2014, *International Journal of Applied Earth Observation and Geoinformation* 68:180–188. https://doi.org/10.1016/j.jag.2017.12.011.

Gubler, D. J., P. Reiter, K. L. Ebi, W. Yap, R. Nasci and J. A. Patz. 2001. Climate variability and change in the United States: Potential impacts on vector- and rodent-borne diseases. *Environmental Health Perspectives* 109(suppl 2):223–233. https://doi.org/10.1289/ehp.109-1240669.

Hamlington, B. D., T. Frederikse, R. S. Nerem, J. T. Fasullo and S. Adhikari. 2020. Investigating the acceleration of regional sea level rise during the satellite altimeter era. *Geophysical Research Letters* 47(5):e2019GL086528. https://doi.org/10.1029/2019GL086528.

Hatfield, J. L. 1983. Remote sensing estimators of potential and actual crop yield. *Remote Sensing of Environment* 13:301–311.

Huffman, G., D. Bolvin, D. Braithwaite, K. Hsu, R. Joyce and P. Xie. 2014. Integrated Multi-satellitE Retrievals for GPM (IMERG), version 4.4. NASA's Precipitation Processing Center. NASA Goddard Space Flight Center Greenbelt, MD. <https://gpm.nasa.gov/data/imerg> (last date accessed: 20 Jan 2025).

Johnson, D. M., A. Rosales, R. Mueller, C. Reynolds, R. Frantz, A. Anyamba, E. Pak and C. Tucker. 2021. USA crop yield estimation with MODIS NDVI: Are remotely sensed models better than simple trend analyses? *Remote Sensing* 13(21):4227. https://doi.org/10.3390/rs13214227.

Jutla, A. S., A. S. Akanda and S. Islam. 2010. Tracking cholera in coastal regions using satellite observations. *Journal of American Water Resources Association* 46(4):651–662. https://doi.org/1111/j.1752-1688.2010.00448.x.

Karnieli, A., N. Agam, R. T. Pinker, M. Anderson, M. L. Imhoff, G. G. Gutman, N. Panov and A. Goldberg. 2010. Use of NDVI and land surface temperature for drought assessment: Merits and limitations. *Journal of Climate* 23:618–633. https://doi.org/10.1175/2009JCLI2900.1.

Landsat Science. 2023. Fifteen Years of Open Data Allows Advancements in Landsat Use and Research, NASA Goddard Space Flight Center Greenbelt, MD. <https://landsat.gsfc.nasa.gov/article/fifteen-years-of-open-data-allows-advancements-in-landsat-use-and-research/> (last date accessed: 15 May 2025).

LandsatNext. 2025. LandsatNext: A New and Revolutionary Mission. NASA Goddard Space Flight Center Greenbelt, MD. <https://landsat.gsfc.nasa.gov/satellites/landsat-next/> (last date accessed: 20 Jan 2025).

Lange, P. K., P. J. Werdell, Z. K. Erickson, D. Dall'Olmo, R.J.W. Brewin, M. V. Zubkov, G. A. Tarran, H. A. Bouman, W. H. Slade, S. E. Craig, N. J. Poulton, A. Bracher, M. W. Lomas, and I. Cetinić. 2020. Radiometric Approach for the Detection of Picophytoplankton Assemblages across Oceanic Fronts. NASA Goddard Space Flight Center Greenbelt, MD. <https://ntrs.nasa.gov/api/citations/20205006419/downloads/Langeetal2020OEmanuscriptv4.docx.pdf> (last date accessed: 20 Jan 2025).

Linthicum, K. J., A. Anyamba, C. J. Tucker, P. W. Kelley, M. F. Myers, and C. J. Peters. 1999. Climate and satellite indicators to forecast Rift Valley fever epidemics in Kenya. *Science* 285:397–400. https://doi.org/10.1126/science.285.5426.397.

Liu, P.-W., R. Bindlish, B. Fang, V. Lakshmi, P. O'Neill, Z. Yang, M. Cosh, T. Bongiovanni, D. Bosch, C. Holifield Collins, P. Starks, J. Prueger, M. Seyfried and S. Livingston. 2020. Assessing disaggregated SMAP soil moisture product in the United States. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing.* 14:2577–2592. https://doi.org/10.1109/JSTARS.2021.3056001.

Loomis, J. B., S. R. Koontz and A. Ravichandran. 2024. Economic valuation of Landsat and Landsat Next 2023. U.S. Geological Survey. <https://www.usgs.gov/media/files/economic-valuation-landsat-and-landsat-next-2023> (last date accessed: 20 Jan 2025)

McClain, C. R., B. A. Franz and P. J. Werdell. 2022. Genesis and evolution of NASA's satellite ocean color program. *Frontiers in Remote Sensing* 3:938006. https://doi.org/10.3389/frsen.2022.938006.

McKibben, S.M., S. Schollaert Uz, and S. Palacios. 2024. Testing a hyperspectral, bio-optical approach to identification of phytoplankton community composition in the Chesapeake Bay, *Earth and Space Science*, https://doi.org/10.1029/2023EA003244

McPhaden, M.J. 1999. Genesis and Evolution of the 1997-1998 El Nino. Science, 283, 950-954. https://doi.org/10.1126/science.283.5404.950

NASA. 2024. Earth Science to Action Strategy. <https://science.nasa.gov/earth-science/earth-science-to-action/> (last date accessed: 20 Jan 2025).

NASA. 2025. Temperatures Rising: NASA Confirms 2024 Warmest Year on Record. <https://www.nasa.gov/news-release/temperatures-rising-nasa-confirms-2024-warmest-year-on-record/> (last date accessed: 23 May 2025).

NASA EarthData. 2024. NASA's Surface Water and Ocean Topography (SWOT) Mission Data Release. <https://www.earthdata.nasa.gov/news/feature-articles/nasas-surface-water-ocean-topography-swot-mission-data-release#toc-altimetry-and-beyond> (last date accessed: 20 Jan 2025).

NASA–Physical Oceanography Distributed Active Archive Center. 2025. Ocean Temperature, Jet Propulsion Lab Physical Oceanography Distributed Active Archive Center. <https://podaac.jpl.nasa.gov/SeaSurfaceTemperature> (last date accessed: 20 Jan 2025).

NASA-TM-84202. 1981. AgRISTARS: Agriculture and resources inventory surveys through aerospace remote sensing, Annual Report FY1980. <https://ntrs.nasa.gov/citations/19820015733> (last date accessed: 20 Jan 2025).

Nerem, R. S., B. D. Beckley, J. T. Fasullo, B. D. Hamlington, D. Masters and G. T. Mitchum. 2018. Climate-change-driven accelerated sea-level rise detected in the altimeter era, *Proceedings of the National Academy of Sciences* 115(9):2022–2025. https://doi.org/10.1073/pnas.1717312115.

Philander, S.G.H. 1992. Ocean-Atmosphere Interactions in the Tropics: A Review of Recent Theories and Models. *Journal of Applied Meteorology* 31: 938-945. https://doi.org/10.1175/1520-0450(1992)031<0938:OAIITT>2.0.CO;2

Rienecker, M. M., M. J. Suarez, R. Todling, J. Bacmeister, L. Takacs, H. C. Liu, W. Gu, M. Sienkiewicz, R. D. Koster, R. Gelaro, I. Stajner and E. Nielsen. 2008. The GEOS-5 Data Assimilation System–Documentation of Versions 5.0.1, 5.1.0, and 5.2.0. Technical Report Series on Global Modeling and Data Assimilation 104606, V27.

Rienecker, M. M., M. J. Suarez, R. Gelaro, R. Todling, J. Bacmeister, E. Liu, M. G. Bosilovich, S. D. Schubert, L. Takacs, G.-K. Kim, S. Bloom, J. Chen, D. Collins, A. Conaty, A. da Silva, W. Gu, J. Joiner, R. D. Koster, R. Lucchesi, A. Molod, T. Owens, S. Pawson, P. Pegion, C. R. Redder, R. Reichle, F. R. Robertson, A. G. Ruddick, M. Sienkiewicz and J. Woollen. 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. *Journal of Climate* 24:3624–3648. https://doi.org/10.1175/JCLI-D-11-00015.1.

Reisen, W. K., R. P. Meyer, S. B. Presser and J. L. Hardy. 1993. Effect of temperature on the transmission of Western equine encephalomyelitis and St. Louis encephalitis viruses by *Culex tarsalis* (Diptera, Culicidae). *Journal of Medical Entomology* 30:151–160

Román, M. O., Z. Wang, Q. Sun, V. Kalb, S. D. Miller, A. Molthan, L. Schultz, J. Bell, E. C. Stokes, B. Pandey, K. C. Seto, D. Hall, T. Oda, R. E. Wolfe, G. Lin, N. Golpayegani, S. Devadiga, C. Davidson, S. Sarkar, C. Praderas, J. Schmaltz, R. Boller, J. Stevens, O. M. Ramos González, E. Padilla, J. Alonso, Y. Detrés, R. Armstrong, I. Miranda, Y. Conte, N. Marrero, K. MacManus, T. Esch and E. J. Masuoka. 2018. NASA's Black Marble nighttime lights product suite. *Remote Sensing of Environment* 210:113–143, https://doi.org/10.1016/j.rse.2018.03.017.

Schollaert Uz, S., A. J. Busalacchi, T. M. Smith, M. N. Evans, C. W. Brown and E. C. Hackert. 2017. Interannual and decadal variability in tropical Pacific chlorophyll from a statistical reconstruction: 1958–2008, *Journal of Climate* 30(18):7293–7315. https://doi.org/10.1175/JCLI-D-16-0202.1.

Schollaert Uz, S., G. E. Kim, A. Mannino, P. J. Werdell and M. Tzortziou. 2019. Developing a community of practice for applied uses of future PACE data to address marine food security challenges. *Frontiers in Earth Science* 7:283. https://doi.org/10.3389/feart.2019.00283.

Schollaert Uz, S., K. C. Stover, S. L. Smith, et al., 2025, Applying global NASA data to local planning for extreme heat in Prince George's County, Maryland. *Innovations in Climate Resilience, Volume II, Frontiers in Environmental Science, Interdisciplinary Climate Studies*, https://doi.org/10.3389/fenvs.2025.1561526.

Stackhouse, P. W., S. K. Gupta, S. J. Cox, T. Zhang, J. C. Mikovitz and L. M. Hinkelman. 2011. 24.5-Year SRB data set released. *GEWEX News* 21(1):10–12.

Su, W., T. P. Charlock, F. G. Rose and D. Rutan. 2007. Photosynthetically active radiation from clouds and the earth's radiant energy system (CERES) products. *JGR Biogeosciences* 112(G2): G02022. https://doi.org/10.1029/2006JG000290.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* 8:127–150

Tucker, C. J., B. N. Holben, J. H. Elgin and J. E. McMurtrey. 1980. Relationship of spectral data to grain yield variation. *Photogrammetric Engineering and Remote Sensing* 46:657–666.

Werdell, P. J., M. J. Behrenfeld, P. S. Bontempi, E. Boss, B. Cairns, G. T. Davis, B. A. Franz, U. B. Gliese, E. T. Gorman, O. Hasekamp, K. D. Knobelspiesse, A. Mannino, J. V. Martins, C. R. McClain, G. Meister, and L. A. Remer. 2019. The plankton, aerosol, cloud, ocean Ecosystem mission: Status, science, advances. *Bulletin of the American Meteorological Society* 100(9):1775–1794. https://doi.org/10.1175/bams-d-18-0056.1.

Wimberly, M. C., A. Lamsal, P. Giacomo and T. Chuang. 2014. Regional variation of climatic influences on West Nile virus outbreaks in the United States. *American Journal of Tropical Medicine and Hygiene* 91:677–684. https://doi.org/10.4269/ajtmh.14-0239.

U.S. Department of Agriculture, Foreign Agricultural Service International Production Assessment Division. 2025. *World Agricultural Production Circular*. <https://ipad.fas.usda.gov/Default.aspx> (last date accessed: 20 Jan 2025).