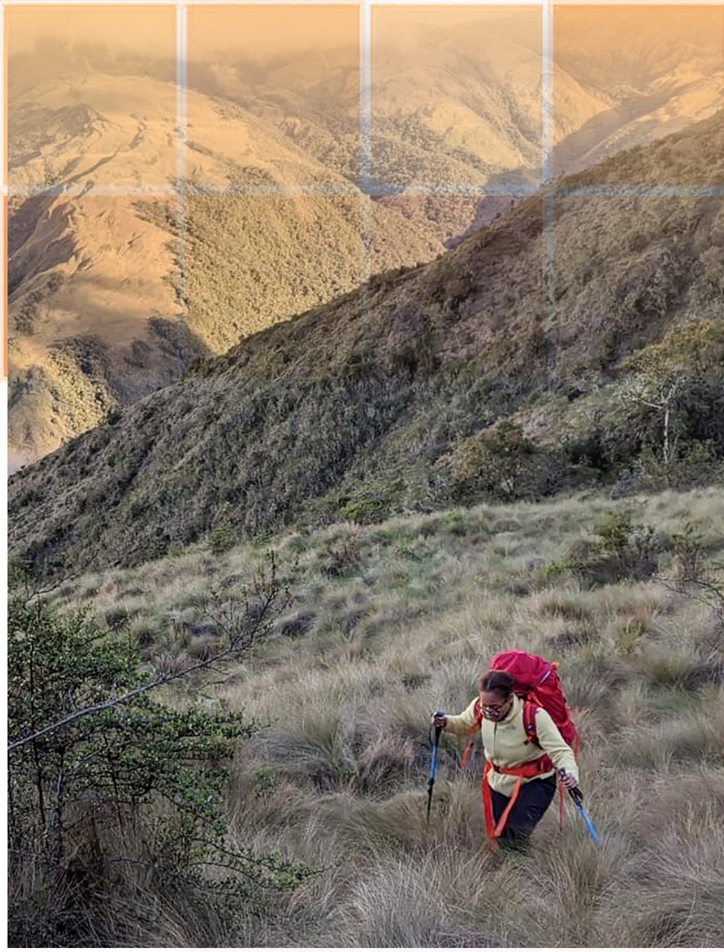
National Aeronautics and Space Administration

PROFILES OF NASA EARTH SCIENCE DATA USERS

2020 YEAR BOOK



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COVER: ***(Upper left)*** Dr. Eric Bullock, ***(Lower left)*** Dr. Eric Sproles, ***(Center top)*** Dr. Emily fischer, ***(Center bottom)*** Dr. Faisal Hossain, ***(Lower right)*** Dr. Sparkle Malone

NASA's Earth Observing System Data and Information System (EOSDIS) is pleased to present the *2020 EOSDIS Data User Profile Yearbook*. The 12 data users you'll read about in this year's edition are using Earth science data in the EOSDIS collection to support research in areas ranging from the Amazon rainforest to the New Zealand Alps and using data acquired from shallow ocean waters to quasars billions of light years from Earth. You'll read about how EOSDIS data are an integral component of research into ecosystem development, food security, public health, and much more.

The EOSDIS Data User Profile series showcases not only the work and research of scientists, researchers, managers, and educators using NASA data, but also the data products that help enable this work. The stories presented here only scratch the surface of the tremendous opportunities created by data that are freely and openly available to anyone anywhere in the world.

For more than 30 years, NASA's EOSDIS has provided long-term measurements of our dynamic planet. The thousands of unique data products in the EOSDIS collection come from a variety of sources, including the International Space Station, satellites, airborne campaigns, field campaigns, *in situ* instruments, and model outputs. These data are managed by NASA's Earth Science Data and Information System (ESDIS) Project and are archived at and distributed by discipline-specific Distributed Active Archive Centers (DAACs) to a diverse worldwide user community.

We hope the following examples of the work being done using data in NASA's EOSDIS collection will stimulate your own investigations into our dynamic planet.

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All profiles written by Josh Blumenfeld, NASA EOSDIS Science Writer

Who Uses Earth Science Data?

Ocean color data provide key information about ocean health. Dr. Barnes uses these data in his investigations into the health of optically shallow waters.

Image of Dr. Barnes by Jamie Inman, Jamie Scarlett Photography.

Dr. Brian Barnes

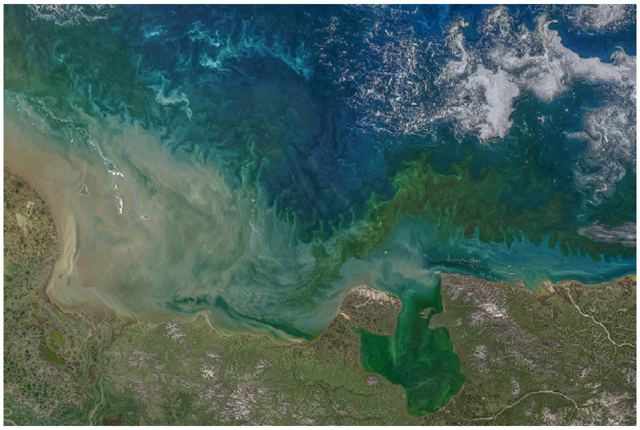
Research Associate, College of Marine Science, University of South Florida, St. Petersburg, FL

Research interests: Using satellite-acquired ocean color data (often combined with *in situ* data) to assess, monitor, and make inferences about the health of shallow coastal environments, including coral reefs, seagrass beds, and oyster reefs.

Research highlights: Gazing out at the open sea on a calm day, the view often is of a uniform body of water with gently undulating waves. But looks can be deceiving. When it comes to the ocean, what matters most is found under the waves. Revealing the secrets – and the science – under the waves in optically shallow waters is a job perfectly suited for sensors aboard Earth observing satellites.

As noted by Dr. Brian Barnes, *optically shallow waters* describe locations where the water is clear and shallow enough that the seafloor is detectable to an above-water radiometer (or light sensor). Such sensors can be carried aboard orbiting satellites, mounted aboard aircraft, or even held by scientists. Although optically shallow waters make up only a fraction of the oceans as a whole, a huge portion of the ocean's productivity and diversity occurs in these regions.

This is because the main driver of ocean primary productivity is sunlight. As on land, the base of the ocean food chain includes organisms that convert sunlight into energy through the process of photosynthesis, such as phytoplankton and macroalgae like *Sargassum*. When these organisms go through periods of extremely high abundance and productivity (called a *bloom*), their presence can be detected by sensors and appear as colored areas in satellite imagery. These ocean color data provide important information about ocean health.



The green and blue/green swirls of color in this Aqua/MODIS image of the East Siberian Sea acquired on July 20, 2020, are phytoplankton, suspended sediments, and dissolved organic matter. A warmer than normal summer led to increased phytoplankton abundance, which is clearly seen in this true-color image. Image from the Ocean Color Image Gallery at NASA's OB.DAAC. https://oceancolor.gsfc.nasa.gov/gallery/712/.

Ocean productivity, color, and biology data are an integral part of NASA's Earth Observing System Data and Information System (EOSDIS) collection. The acquisition, processing, calibration, and validation of these products is done by NASA's Ocean Biology Processing Group (OBPG), and these products are freely available to scientists like Dr. Barnes through NASA's EOSDIS Ocean Biology Distributed Active Archive Center (OB.DAAC).

Dr. Barnes uses ocean color data from numerous sensors and missions (many of which are available through OB.DAAC) to investigate shallow coastal environments, such as coral reefs, seagrass beds, and oyster reefs. Interpreting satellite-collected ocean color data, though, is not without difficulty. As Dr. Barnes notes, one problem ocean color researchers face is that the energy detected by a satellite sensor includes contributions from the atmosphere, the water column, and even the substrate and organisms living on the ocean floor (an area called

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the benthic zone, or benthos). By separating these three contributions, researchers can assess water quality in optically shallow waters and the health of benthic environments.

In recent studies, Dr. Barnes and his colleagues used a variety of data collection methods to examine the impacts to coral and other aquatic ecosystems from dredging activities at large ports, such as the Port of Miami (which is branded as PortMiami). The dredging of ports to accommodate large ships and keep shipping lanes open creates tremendous disturbances to shallow water ecosystems. This dredging also stirs up sediments that can change the color of areas being dredged, which can be detected by sensors aboard satellites.

Dredging of PortMaimi in 2013 created large concentrations of suspended sediments in the water column, called turbidity plumes. Since these plumes could be observed in the satellite data record, Dr. Barnes and his colleagues developed methods to quantify these plumes as they developed over time. The research team coupled these analyses with historical data collected from *in situ* sensors, such as National Data Buoy Center (NDBC) buoys in and around PortMiami. Since turbidity plumes naturally occur in most coastal systems (strong winds, for example, can stir-up and suspend sediments), the combination of satellite imagery with *in situ* buoy data enabled the team to quantify the size and frequency of plumes that were beyond what would be expected to naturally occur in and around PortMiami.

Dr. Barnes (on right) and a colleague install an optical water quality sensor at a coral nursery in the Florida Keys. Along with satellite-acquired data, Dr. Barnes uses a variety of field-collected data in his research. Image by Tim Grollimund.

The team also used a combination of satellite ocean color data and *in situ* measurements to examine the impact to several threatened species of coral in reefs near PortMiami. Coupling satellite-collected data with physical measurements of coral burial and other criteria during the dredging, Dr. Barnes was able to identify huge areas of reef that were impacted – potentially to the point of coral mortality. Stemming from this work, the U.S. Environmental Protection Agency (EPA) asked the research team to establish satellite-derived baseline turbidity conditions for an upcoming dredging project north of PortMiami. This baseline can be used for near real-time monitoring of anomalies resulting from the dredging. Dr. Barnes and his colleagues also used similar methods in a 2016 study examining impacts from island building activities in the South China Sea.

In a larger research project, Dr. Barnes is part of a team exploring changes in the abundance and distribution of a floating macroalgae called *Sargassum* in the central Atlantic Ocean (doi: 10.1126/science.aaw7912). *Sargassum* naturally occurs in the Central Atlantic, where it forms floating mats large enough to be detected in satellite imagery. Many ocean species rely on these floating mats for shelter, food, nursery areas, breeding grounds, and other basic functions. When *Sargassum* blooms collect near or onshore, however, they can have ecologic and economic consequences. Ecologically, *Sargassum* blooms can smother benthic environments; economically, the blooms can impact tourism as they rot and emit a foul odor, and can be expensive to remove from beaches and other public areas.

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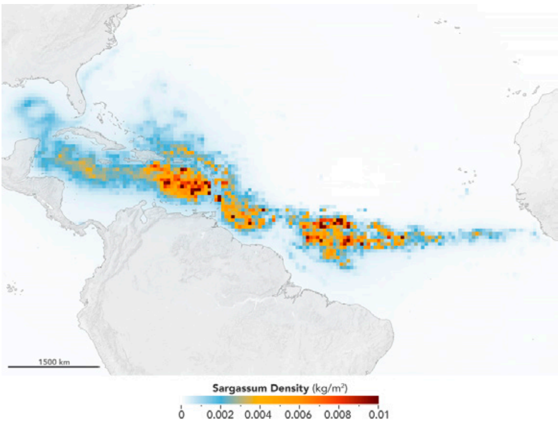
Since 2011, a Great Atlantic Sargassum Belt (GASB) has been observed in satellite imagery. These recurring huge blooms of *Sargassum* cover an area that can stretch almost 9,000 km (almost 5,600 miles). Led by Dr. Mengqiu Wang at the University of South Florida (USF), Dr. Barnes has been heavily involved in a team working to predict the movement of the GASB and its potential to impact shorelines.



The GASB in July 2018. Dr. Barnes was part of the team that used data acquired by the MODIS instrument aboard NASA's Aqua satellite to discover the GASB. With the exception of 2013, the GASB has formed every year since 2011, and often stretches from the west coast of Africa to the Gulf of Mexico. Image: NASA/Earth Observatory and based on data provided by Mengqiu Wang and Chuanmin Hu, USF College of Marine Science.

An important resource in this work is the almost 20-year record of daily global imagery acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Aqua satellite (launched in 2002). The daily MODIS imagery enabled the team to not only track the movement of the GASB, but also its origins. Combining MODIS imagery with sea surface temperature (SST) data, the team found that recent bloom events show connections to nutrient enrichment and climatic variations. Remotely sensed data also enabled the team to determine that one source of nutrient enrichment in the central west Atlantic Ocean was increased deforestation and fertilizer use in Brazil. These activities have increased the amount of nitrogen in the water column, stimulating *Sargassum* blooms.

While much of Dr. Barnes' work utilizes Aqua/MODIS data and imagery, this instrument has been in orbit since 2002 and already has far exceeded its predicted life span. Fortunately, MODIS is not the only orbiting sensor collecting ocean color data. The Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP; launched in 2011) and NOAA-20 (launched in 2017) satellites, the Ocean and Land Colour Instrument (OLCI) aboard the ESA (European Space Agency) Sentinel-3 A and B satellites (launched in 2016 and 2018, respectively), and NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) aboard the SeaStar satellite (operational 1997 to 2010) all provide(d) valuable ocean color data.

Dr. Barnes is part of the team developing applications for the next generation of ocean color sensors: the Ocean Color Instrument (OCI). The OCI is the primary sensor aboard NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite, which is scheduled for launch in 2022. The OCI will be the most advanced ocean color sensor ever launched by NASA. What sets the OCI apart from other ocean color sensors is that it will detect radiation along a very broad spectrum of wavelengths at 5 nanometer (nm) intervals, including the ultraviolet (UV) (350-400 nm), visible (400-700 nm), and near infrared (700-885 nm), as well as several shortwave infrared bands. While heritage sensors are multi-spectral (collecting measurements at a few discrete wavelengths), OCI is hyperspectral, and collects continuous measurements across the visible light spectrum. As PACE Project Scientist Dr. Jeremy Werdell observes, heritage sensors are like a crayon box with eight colors; OCI is the 64-crayon box that we all wanted as kids. The result will be a sensor providing an unprecedented view of the ocean without the sensor wavelength blind spots of previous satellite-borne sensors.

Thanks to the next generation of ocean color sensors, we are on the verge of a new era of investigation in exploring ocean science. Through the work of scientists like Dr. Barnes, these data and discoveries soon will be part of NASA's ever-growing EOSDIS collection.

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Representative data products used; available through OB.DAAC:

- Aqua/MODIS products:
  - Level 2, Sea Surface Temperature (SST; doi: 10.5067/AQUA/MODIS/L2/SST/2014)
  - Level 2, Inherent Optical Properties (IOP; doi: 10.5067/AQUA/MODIS/L2/IOP/2018)
  - Level 2, Ocean Color (OC; doi: 10.5067/AQUA/MODIS/L2/OC/2018)
  - Level 3B (multiple products)
- Suomi NPP/VIIRS products:
  - Level 2, IOP (doi: 10.5067/NPP/VIIRS/L2/IOP/2018)
  - Level 2, OC (doi: 10.5067/NPP/VIIRS/L2/OC/2018)
- Earth observation Full Resolution (EFR) and Earth observation Reduced Resolution (ERR) data from the Ocean and Land Colour Instrument (OLCI) aboard ESA's Sentinel-3 A and Sentinel-3 B satellites

Read about the research:

Barnes, B.B., Hu, C., Bailey, S.W. & Franz, B.A. (2020). "Sensitivity of Satellite Ocean Color Data to System Vicarious Calibration of the Long Near Infrared Band." *IEEE Transactions on Geoscience and Remote Sensing* [doi: 10.1109/tgrs.2020.3000475].

Gray, E. (2019). "NASA Satellites Find Biggest Seaweed Bloom in the World." NASA's Earth Science News Team. Published July 8, 2019, and available online at https://go.nasa.gov/3jFnesP.

Wang, M., Hu, C., **Barnes, B.B.,** Mitchum, G. & Lapointe, B. (2019). "The Great Atlantic *Sargassum* Belt." *Science,* 365(6448): 83-87 [doi: 10.1126/science.aaw7912].

Cunning, R., Silverstein, R.N., **Barnes, B.B.** & Baker, A.C. (2019). "Extensive coral mortality and critical habitat loss following dredging associated with remotely-sensed sediment plumes." *Marine Pollution Bulletin,* 145: 185-199 [doi: 10.1016/j.marpolbul.2019.05.027].

Published October 29, 2020

Who Uses Earth Science Data?

Deforestation is taking a toll on the Amazon and other areas of high biodiversity. Dr. Eric Bullock uses Earth observation data to explore the consequences of land use and land cover change in these areas.

Dr. Eric Bullock on the Nanay River outside of Iquitos, Peru, in the Peruvian Amazon. Image courtesy of Dr. Bullock.

Dr. Eric Bullock

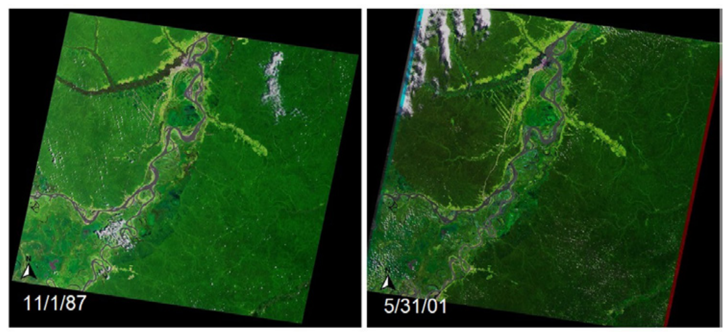
Post-Doctoral Researcher; Center for Remote Sensing, Boston University, Boston, MA

Research interests: Using remotely-sensed data to address issues related to land cover and land use change, including the role of forest disturbance in the terrestrial carbon cycle, the resiliency of mangroves to climate change, the effectiveness of protected areas, and applications for international greenhouse gas reporting mechanisms.

Research highlights: The city of Iquitos, Peru, sits hard against the Amazon rainforest. Accessible only by boat or air, this city of nearly 500,000 people has for centuries been a gateway to the Amazon. Its location along the Amazon River facilitates the flow of timber, oil, rubber, and other natural resources out of one of the most biodiverse regions on Earth.

Until the late-20th century the Amazon was able to push back. Its lack of accessibility limited deforestation in Peru to roughly 0.2% to 0.4% annually, according to the Global Forest Atlas. By the start of the 21st century, though, an illegal timber trade had exploded and deforestation is increasing.

These disturbances to the Amazon are also leading to changes in this vast region's ecology that can be tracked by instruments aboard Earth observing satellites. Disturbances such as openings in the understory from deforestation that allow new plant species to move in and shifts in reflectance as green vegetation is replaced with brown earth can be detected from space. As Dr. Eric Bullock notes, remotely-sensed data enable the detection and monitoring of subtle changes in forest ecosystems.



Landsat images from NASA's Science Visualization Studio (SVS) of Iquitos, Peru, showing deforestation and degradation of the region over time. ***Left image*** acquired November 1, 1987, by Landsat 5. ***Right image*** acquired May 31, 2001, by Landsat 7. Note the greater extent of lighter green areas in the 2001 image indicating deforested and degraded areas. Click on image for larger view. Both images NASA/Goddard Space Flight Center SVS. View an animation of these images at https://svs.gsfc.nasa.gov/2678.

In his research into land use change and the role of tropical forests in the global carbon cycle, Dr. Bullock relies on data in NASA's Earth Observing System Data and Information System (EOSDIS) collection. His primary source for these EOSDIS data is NASA's Land Processes Distributed Active Archive Center (LP DAAC). LP DAAC is a partnership between NASA and the USGS, and provides tools and services for discovering and analyzing EOSDIS data related to areas including land cover and land use. LP DAAC is part of the USGS Earth Resources Observation and Science (EROS) Center in Sioux Falls, SD, which distributes data from the joint NASA/USGS Landsat series of satellites that Dr. Bullock also incorporates in his research.

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Who Uses Earth Science Data?

Using Landsat data, Dr. Bullock developed the open source Continuous Degradation Detection (CODED) algorithm for mapping tropical forest degradation and deforestation using time series analysis of Landsat data. The motivation behind the CODED project was to develop a methodology that could successfully identify low-magnitude forest disturbances and help better differentiate between deforestation and degradation. When applying the CODED methodology to the Amazon Ecoregion, Dr. Bullock and his colleagues found that since 1995 approximately the same amount of forest has been affected by degradation as has been affected by deforestation due to causes such as fire and selective logging. Consequently, the research team found that the Amazon is 44% to 60% more disturbed than previously reported, corresponding to unaccounted carbon emissions and damage to critical ecosystems.

Dr. Bullock looking at historical Landsat data in the Amazon near Iquitos, Peru. Thanks to a Global Positioning System (GPS) hooked up to the computer and a hard drive containing Landsat data, Dr. Bullock is looking at data for the location at which he is standing. These data are helping fine-tune the CODED algorithm for mapping degradation and deforestation across the Amazon Ecoregion. For more information about this research, please see Bullock, E.L., et al. (2020), doi:10.1111/gcb.15029.

Dr. Bullock is piloting the CODED methodology for use as part of the United Nations Reducing Emissions from Deforestation and Degradation in Developing Countries (REDD+) program (the "+" stands for "plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks"). REDD+ is a United Nations initiative created to reduce emissions from deforestation and forest degradation, and offers financial incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. REDD+ activities are taking place in 64 countries, and Dr. Bullock has taught his CODED methodology in South America, Africa, and Southeast Asia in support of REDD+ activities.

Dr. Bullock also utilizes near real-time (NRT) data in his work. He was part of a team that used daily data acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Terra (launched in 1999) and Aqua (launched in 2002) Earth observing satellites to create automated NRT alerts for new areas of deforestation. This is an important element in deforestation monitoring since, as the research team notes, rapid detection of deforestation events is vital for preventing future forest losses and for mitigating the negative effects of deforestation, such as increased carbon emissions, detrimental environmental impacts, and the endangerment of native and local communities.

NASA's EOSDIS provides access to numerous NRT products, including MODIS NRT products, through NASA's Land, Atmosphere Near real-time Capability for EOS (LANCE). Since MODIS acquires full global data and imagery every one-to-two days, it provides excellent spatial and temporal coverage. Its frequency of coverage also ensures enough cloud-free images to enable rapid assessment and comparison of specific areas of interest over days, months, or years.

Dr. Bullock and his colleagues created two algorithms using MODIS data. The first algorithm, NRT-Continuous Change Detection and Classification (NRT-CCDC), is based on an existing CCDC algorithm using MODIS data that has been used for land cover monitoring in New England, China, and Columbia. The research team modified the CCDC algorithm to focus on NRT disturbance detection, with detected disturbances labeled as low-probability, high-probability, or confirmed based on the number of consecutive

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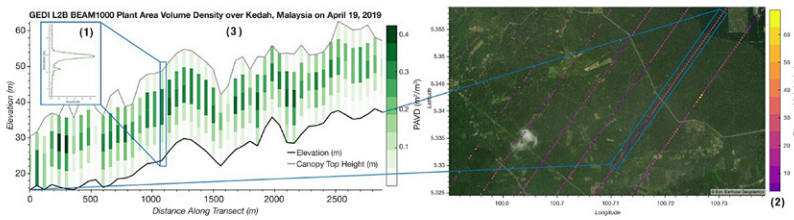
observations exceeding a change threshold, with an alert triggered for detected low- and high-probability disturbances.

The second algorithm, called Fusion2, utilizes daily Terra and Aqua MODIS observations to rapidly detect disturbance using a model based on a time series of Landsat observations. The research team found that both the NRT-CCDC and Fusion2 algorithms showed higher performance detecting large deforestation events than small events and that the Fusion2 algorithm detects forest disturbance slightly more rapidly than the NRT-CCDC algorithm.



Example of GEDI data acquired during a pass over Kedah, Malaysia, on April 19, 2019. ***Right image*** shows track of GEDI LiDAR pulses over the ground. ***Left image*** shows a representation of the returned waveform data. Solid line at bottom of bars in left image indicates ground elevation; lighter line at top of bars indicates canopy height; colors within bars indicate Plant Area Volume Density (PAVD), with darker green indicating higher PAVD values. Image courtesy of NASA's LP DAAC.

New data relevant to land use and land cover studies are constantly being added to the EOSDIS collection, and Dr. Bullock has started working with recently-released data from NASA's Global Ecosystem Dynamics Investigation (GEDI) mission to the International Space Station. Led by the University of Maryland in collaboration with NASA's Goddard Space Flight Center in Greenbelt, MD, GEDI launched on December 5, 2018, and is installed on the space station's Japanese Experiment Module-Exposed Facility (JEM-EF). GEDI is producing high-resolution laser ranging observations of Earth in order to characterize the effects of climate change and land use on ecosystem structure and dynamics. GEDI data are acquired using a light detection and ranging (lidar) laser system that uses laser beam pulses to measure the distance of objects from the laser. When paired with a global positioning system (GPS) receiver, these data can be used to create extremely accurate 3D measurements of Earth.

As noted in a NASA Earthdata article, GEDI data will help further refine our understanding of the carbon cycle and atmospheric concentrations of carbon dioxide (CO_2), and help identify and provide a better understanding of how physical disturbances affect ecosystems and carbon storage. Lower-level (Level 1 and 2) GEDI data currently are available through NASA's LP DAAC; higher-level (Level 3 and 4) GEDI products soon will be available through NASA's Oak Ridge National Laboratory DAAC (ORNL DAAC). ORNL DAAC is a partnership between NASA and the U.S. Department of Energy, and is responsible for EOSDIS data related to biogeochemical dynamics, ecology, and environmental processes.

As Dr. Bullock and his colleagues continue their research into the ecological impacts of deforestation and forest degradation and the challenges of land use changes in the Amazon and other ecoregions, Earth observing satellites also continue their silent journey collecting the remotely-sensed data that help enable this work. Through NASA's EOSDIS, these data are only a mouse-click away.

Representative data products used:

- Available through LP DAAC:
    - Terra/MODIS Surface Reflectance Daily L2G Global 250 m SIN Grid (doi: 10.5067/MODIS/MOD09GQ.006)

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- Aqua/MODIS Surface Reflectance Daily L2G Global 250 m SIN Grid (doi: 10.5067/MODIS/MYD09GQ.006)
- Terra/MODIS Vegetation Indices 16-Day L3 Global 250 m SIN Grid (doi: 10.5067/MODIS/MOD13Q1.006)
- Aqua/MODIS Vegetation Indices 16-Day L3 Global 250 m SIN Grid (doi: 10.5067/MODIS/MYD13Q1.006)
- GEDI L2B Canopy Cover and Vertical Profile Metrics Data Global Footprint Level (doi: 10.5067/GEDI/GEDI02_B.001)

- Landsat Collection 1, various datasets; available through the USGS EROS Center and the USGS EarthExplorer online search, discovery, and ordering tool

Read about the research:

Bullock, E.L., Woodcock, C.E., Souza Jr., C. & Olofsson, P. (2020). "Satellite-based estimates reveal widespread forest degradation in the Amazon." *Global Change Biology,* 26(5): 2956-2969 [doi: 10.1111/gcb.15029].

Bullock, E.L., Woodcock, C.E. & Holden, C.E. (2020). "Improved change monitoring using an ensemble of time series algorithms." *Remote Sensing of Environment,* 238: 111165 [doi: 10.1016/j.rse.2019.04.018].

Tang, X., **Bullock, E.L.,** Olofsson, P., Estel, S. & Woodcock, C.E. (2019). "Near real-time monitoring of tropical forest disturbance: New algorithms and assessment framework." *Remote Sensing of Environment,* 224: 202-218 [doi: 10.1016/j.rse.2019.02.003].

Bullock, E.L., Woodcock, C.E. & Olofsson, P. (2018). "Monitoring tropical forest degradation using spectral unmixing and Landsat time series analysis." *Remote Sensing of Environment,* 238: 110968 [doi: 10.1016/j.rse.2018.11.011].

Published May 28, 2020

Who Uses Earth Science Data?

Our atmosphere is a chemical soup that is constantly sampled by orbiting Earth observing satellites. Dr. Emily Fischer uses these data to better understand how pollutants move in the lower atmosphere.

Dr. Fischer (*right*) confers with Dr. Frank Flocke prior to a flight of the NSF/NCAR C-130 research aircraft as part of the WE-CAN field campaign in Idaho during the summer of 2018. Image by Bill Cotton and courtesy of Dr. Fischer.

Dr. Emily Fischer

Associate Professor, Department of Atmospheric Science and School of Global Environmental Sustainability; Colorado State University, Fort Collins, CO

Research interests: Using satellite observations, ground-based and airborne measurements, and chemical transport models to describe the sources, fate, and impacts of pollutants in lower levels of Earth's atmosphere.

Research highlights: Ozone (written chemically as "O_3" to designate that it is made up of three oxygen atoms) is a pretty amazing molecule. It is highly reactive, which means it easily can be broken into components of individual molecules of atomic oxygen (O) or into molecular oxygen (O_2) and then re-combine back into ozone (O_3). This molecular breaking and re-combining is caused primarily by ultraviolet (UV) radiation from the Sun, and is rapidly and constantly occurring in a layer of the atmosphere called the *stratosphere,* which extends from about 10 to 50 km above Earth's surface. Through this process, most of the Sun's harmful UV radiation is absorbed and prevented from reaching lower levels of the atmosphere (check out the frightening results of a NASA model simulation predicting what could happen if Earth's stratospheric ozone were depleted). Fortunately for life on Earth, 90% of atmospheric ozone is in the stratosphere.

The remaining 10% of Earth's ozone resides in the lowest layer of the atmosphere, called the *troposphere*, which extends from the surface to about 10 km. This is where the whole breaking and recombining of ozone molecules becomes more complex – and more interesting for researchers like Dr. Emily Fischer. Using satellite-derived Earth observing data from NASA's Earth Observing System Data and Information System (EOSDIS) collection combined with model data and data acquired through field investigations and aircraft-borne instruments, Dr. Fischer and her colleagues are exploring how a trace gas called peroxyacetyl nitrate (commonly known as *PAN*) impacts the distribution of ozone in the troposphere.

In the lower atmosphere, PAN and ozone are two important pollutants, particularly in and around urban areas. Both are poisonous to plants in high concentrations, and both can affect human health. PAN is a strong eye and respiratory irritant, and ground-level ozone can cause a wide range of respiratory issues. As noted by the U.S. Environmental Protection Agency (EPA), "long-term exposure to [low-level] ozone is linked to aggravation of asthma, and is likely to be one of many causes of asthma development. Long-term exposures to higher concentrations of ozone may also be linked to permanent lung damage."

Tropospheric ozone forms in a different way than stratospheric ozone. In the troposphere, nitrogen dioxide (NO_2) rather than molecular oxygen (O_2) is the primary source of the oxygen atoms required for ozone formation. Sunlight splits nitrogen dioxide (NO_2) into nitric oxide (NO) and an oxygen atom (O), and this oxygen atom combines with molecular oxygen to form ozone ($O + O_2 = O_3$).

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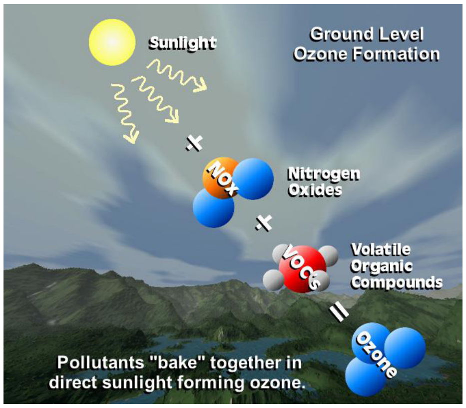
Who Uses Earth Science Data?

Nitrogen dioxide (NO_2) and nitric oxide (NO) are together known as NO_x (pronounced *knocks*). NO_x plays a critical role in many chemical cycles occurring in lower levels of the atmosphere.

NO_x is formed when nitrogen and oxygen react with each other during combustion at high temperatures. Fossil fuel combustion is the principal source of NO_x, but there are additional contributions from biomass burning, lightning, and soils. NO_x can cause serious health problems to humans, including respiratory diseases, and is responsible for smog and the "brown cloud" that can cover large cities and produce poor air quality. NO_x emissions contribute to acid rain and the formation of ground-level ozone.



NASA Aura science team image showing how ozone forms in the lower atmosphere. Volatile organic compounds (VOCs) are carbon-containing chemicals that evaporate easily into the air and are emitted as gases from certain solids or liquids, such as paint, varnish, fuel, and cleaning products.

Which brings us back to PAN. As noted by Dr. Fischer and her colleagues, PAN is the most important reservoir for NO_x in the troposphere and plays a significant role in the redistribution of NO_x to remote regions. This, in turn, has major implications for the global distributions of tropospheric ozone and other pollutants.

Much of the satellite data used by Dr. Fischer in her PAN research were acquired by the Tropospheric Emission Spectrometer (TES) instrument aboard NASA's multi-national Aura satellite. Launched in 2004, Aura acquires measurements of ozone, aerosols, and key gases throughout the atmosphere.

TES collected data between 2004 and its decommissioning in 2018 due to a part failure. Routine standard data products from TES include vertically-resolved profiles for atmospheric ozone (O_3), carbon monoxide (CO), water vapor (H_2O), and methane (CH_4). TES data are also turned into specially processed data products, including atmospheric profiles of ammonia (NH_3) and PAN.

TES data are available through NASA's Atmospheric Science Data Center (ASDC), which is the EOSDIS Distributed Active Archive Center (DAAC) responsible for EOSDIS data related to Earth's radiation budget, clouds, aerosols, and tropospheric composition. As noted by Dr. Fischer in a NASA news release about the TES decommissioning, "TES really paved the way in our global understanding of both PAN and [ammonia], two keystone species in the atmospheric nitrogen cycle."

Dr. Fischer observes that PAN is difficult to measure, and there are large gaps in our knowledge of the distribution, seasonal cycles, and interannual variability of PAN. She was part of a team that worked with researchers at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, to analyze TES-derived tropospheric measurements of PAN that showed how boreal fires are a key source of interannual variability in reactive nitrogen during the spring in high latitudes. She and her colleagues also confirmed that TES is sufficiently sensitive to detect PAN enhancements several days downwind of fires over North America (biomass burning, such as through wildfires, is a significant source of nitrogen).

The next step in Dr. Fischer's research into biomass burning and PAN will be to analyze PAN data from the Cross-Track Infrared Sounder (CrIS) instrument aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership satellite (Suomi NPP; operational 2011 to present). Along with providing detailed atmospheric temperature and moisture observations, CrIS also measures atmospheric chemistry and can detect the concentration of atmospheric greenhouse gases.

(Continued)

Dr. Fischer's objective is to integrate CrIS data with data from a recent National Science Foundation (NSF)-funded airborne campaign on which she was the lead Principal Investigator (PI). The campaign, called the Western Wildfire Experiments for Cloud Chemistry, Aerosol Absorption, and Nitrogen (WE-CAN), took place in the summer of 2018 and used an instrument-laden National Center for Atmospheric Research (NCAR) C-130 aircraft to better understand the impact of Western wildfires on PAN and ozone over North America during summer months. Dr. Fischer's objective is to harness PAN satellite data from both TES and CrIS to close knowledge gaps in our understanding of the sources of NO_x in remote regions of the troposphere.

The chemical ingredients of the lower atmosphere come together using recipes that are slowly being deciphered by researchers like Dr. Fischer. The shopping list for these ingredients come from Earth observing data, many of which are part of NASA's EOSDIS collection.

Representative data products and models used:

- TES/Aura L2 Peroxyacyl Nitrate Lite Nadir V007 (TL2PANLN; doi: 10.5067/AURA/TES/TL2PANLN.007); available through ASDC
- Goddard Earth Observing System Chemistry-Climate Model (GEOS-CCM); available through the Global Modeling and Assimilation Office at NASA's Goddard Space Flight Center in Greenbelt, Maryland
- CrIS data, available through NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC)
- WE-CAN campaign data; available through NCAR

Read about the research:

Fischer, E.V., Zhu, L., Payne, V.H., Worden, J.R., Jiang, Z., Kulawik, S.S., Brey, S., Hecobian, A., Gombos, D., Cady-Pereira, K. & Flocke, F. (2018). "Using TES retrievals to investigate PAN in North American biomass burning plumes." *Atmospheric Chemistry and Physics,* 18(8): 5639-5653 [doi: 10.5194/acp-18-5639-2018].

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Zhu, L., Payne, V.H., Walker, T.W., Worden, J.R., Jiang, Z., Kulawik, S.S. & **Fischer, E.V.** (2017). "PAN in the Eastern Pacific Free Troposphere: A Satellite View of the Sources, Seasonality, Interannual Variability and Timeline for Trend Detection." *Journal of Geophysical Research Atmospheres,* 122(6): 3614-3629 [doi: 10.1002/2016JD025868].

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(Continued)

Fischer, E.V., Jacob, D.J., Yantosca, R.M., Sulprizio, M.P., Millet, D.B., Mao, J., Paulot, F., Singh, H.B., Roiger, A., Ries, L., Talbot, R.W., Dzepina, K. & Pandey Deolal, S. (2014). "Atmospheric peroxyacetyl nitrate (PAN): a global budget and source attribution." *Atmospheric Chemistry and Physics,* 14(5): 2679-2698 [doi: 10.5194/acp-14-2679-2014].

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Who Uses Earth Science Data?

The Global Navigation Satellite System (GNSS) enables the precise location of points on Earth's surface. For geodesists like Dr. Herring, it also is a key geodetic technique for his studies of deformation processes.

Dr. Thomas A. Herring

Professor of Geophysics; Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA

Research interests: Applications and development of geodetic systems, with a current focus on using the Global Navigation Satellite System (GNSS) to study deformation processes on Earth and the medium through which satellite microwave signals propagate.

Research highlights: One of the great achievements of the space age is the Global Navigation Satellite System (GNSS). Haven't heard of GNSS? Chances are you might be more familiar with the name used for the U.S. version of the GNSS constellation of satellites: the Global Positioning System (GPS). The European version of the GNSS constellation is called Galileo, while the Russian constellation is called the GLObal NAvigation Satellite System (GLONASS). China has their BeiDou satellites, Japan the Quasi-Zenith Satellite System (QZSS), and India has the Indian Regional Navigation Satellite System (IRNSS). Through these constellations of Earth-orbiting satellites, the precise location of any point on the planet and, more importantly, the determination of precise changes in location of any point on the planet can be established.

While the national names of GNSS constellations may differ, the technique is the same – satellites in a constellation constantly transmit location and timing data that are detected by ground-based receivers. By using precisely timed signals from at least four satellites in known orbits, the exact position of a receiving station can be determined. As of November 13, 2020, 30 operational satellites comprise the U.S. GPS constellation, according to GPS.gov.

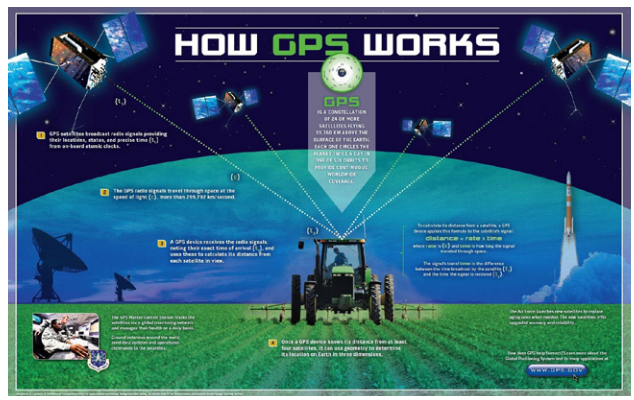
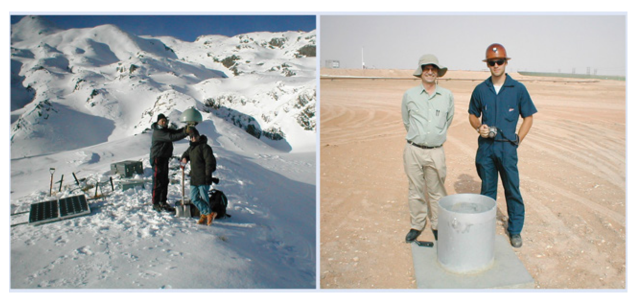


Image from GPS.gov and available for download at https://www.gps.gov/multimedia/poster/poster-web.pdf.

GNSS is one technique in the field of geodesy, which is the science of measuring Earth's geometric shape, its orientation in space, and its gravity field. GNSS is also a key element of geodesist Dr. Thomas Herring's research into deformation processes and how microwave signals from satellites propagate through various media. The deformation processes Dr. Herring studies can be steady (such as the motions of tectonic plates, which move at a rate of three to five centimeters per year, according to National Geographic), transient (such as rapid deformations



Dr. Herring uses GPS in studies around the world. ***Left image:*** Dr. Herring (on right) and a colleague in the New Zealand Southern Alps using GPS to measure vertical uplift across Southern New Zealand (the gray helmet-looking object above Dr. Herring). ***Right image:*** Dr. Herring (on left) and a colleague in Oman using GPS to measure subsidence and horizontal motions due to oil and gas extraction. The canister in front of Dr. Herring protects the GPS antenna, which is inside. Images courtesy of Dr. Herring.

(Continued)

from earthquakes and processes that follow earthquakes), or intermediate (such as the subsidence of land through water pumping or oil extraction that occur on timescales of days to months). He observes that the medium through which the satellite signals propagate can affect the location information of sites on and near Earth's surface and must be accounted for to determine precise location change over time.

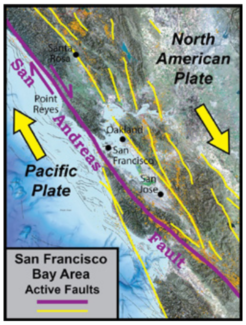
Geodetic data used by Dr. Herring come from a number of sources, including data freely and openly available through NASA's Crustal Dynamics Data Information System (CDDIS). CDDIS is the home of geodetic data in NASA's Earth Observing System Data and Information System (EOSDIS) collection. The data and derived products available through CDDIS come from a global network of observing stations equipped with one or more of the following geodetic techniques:

- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)
- Global Navigation Satellite System (GNSS)
- Satellite Laser Ranging (SLR; including Lunar Laser Ranging (LLR))
- Very Long Baseline Interferometry (VLBI)

CDDIS has served as a global data center for the International GNSS Service (IGS) since 1992, and actively supports the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), the International DORIS Service (IDS), and the International Earth Rotation and Reference Systems Service (IERS) as a global data center.

Along with the GNSS data he acquires from CDDIS, Dr. Herring and his colleagues at the Massachusetts Institute of Technology (MIT) also create their own GNSS data products. These include the GNSS At MIT and Global Kalman filter (GAMIT/GLOBK) software, which is a comprehensive suite of programs for analyzing GNSS measurements primarily to study crustal deformation. Freely available from MIT, GAMIT/GLOBK was developed by MIT, the Harvard-Smithsonian Center for Astrophysics (CfA), the Scripps Institution of Oceanography (SIO), and the Australian National University, with support from the U.S. National Science Foundation and NASA's Earth's Surface and Interior (ESI) focus area.

One of Dr. Herring's recent research projects involves analyzing large datasets collected for studying the North America Pacific plate boundary and the deformations happening in North America and the region around it. A well-known part of this region is along the San Andreas Fault, where a section of western California, as part of the Pacific Plate, slides north-northwestward past the rest of North America. As noted by the USGS, Point Reyes National Seashore, Golden Gate National Recreation Area, and Pinnacles National Park are landscapes shaped by movement of the San Andreas Fault, and Cabrillo National Monument south of San Diego lies within the broad zone of deformation caused as the Pacific Plate slides past the North American Plate. GNSS data enable the precise mapping of this deformation as well as the rate of plate movement.



Active faults and the movement of plate boundaries near San Francisco, CA, USA. A detailed explanation of these plate boundaries is available at https://bit.ly/2J4q9ON. USGS image.

Dr. Herring points out that the steady motions at the plate boundaries indicate how strain and stress are accumulating. Transient phenomena, often referred to as slow slip events (SSE), affect the interaction between the stress building at the plate boundary and

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the release of this stress, which is experienced as an earthquake. The precise relationship between the steady accumulation of stress and the resulting transient phenomena is still being determined, and the ultimate aim of this research is to better understand the processes leading to earthquakes. The GNSS data used in these studies are available through CDDIS along with products generated by the IGS and made available through CDDIS.

GNSS also is useful in studies of how architectural structures, such as tall buildings, radio towers, and similar objects, react to transient phenomena. This is what took Dr. Herring to the top of the tallest building in Kuwait – the 1,355-foot Al Hamra Tower. A GPS system was installed near the top of this sinuously curving skyscraper to study the response of the building to earthquakes and environmental changes. In November 2017, the research team used GPS data to analyze the motions at the top of the building due to a distant magnitude 7.3 earthquake. While motion at ground level was approximately 40 mm, motion at the top of the building was measured at approximately 160 mm. According to the research team, the building responded as expected, although it continued shaking for an extended period of time after the first waves from the earthquake arrived. This research has direct applications for architectural design in earthquake-prone regions and was a collaboration with the Kuwait Institute for Scientific Research (KISR) and the Kuwait Federation for the Advancement of Science (KFAS).

Whether you're trying to measure the movement of a continental plate moving mere centimeters a year or the rapid deformation to land and structures following an earthquake, a constellation of GNSS satellites traveling tens of thousands of miles per hour around Earth makes this possible. The research of Dr. Herring – using data freely available through CDDIS and other sources – is helping make these data even more precise.

Representative data products used or created:

Available through CDDIS:

- Daily GNSS tracking data; Receiver INdependent EXchange (RINEX) format
- IGS and Multi-GNSS experiment (MGEX) orbits and broadcast ephemeris information (doi:10.5067/GNSS/GNSS_IGSMGEXP_001)
- Global ionospheric delay gridded models: IONosphere EXchange (IONEX) format

Products generated by Dr. Herring and his colleagues for distribution through CDDIS:

- GPS orbit, clock, and Solution (Software/technique) INdependent EXchange Format (SINEX) files for IGS final GPS orbits from the MIT IGS Analysis Center (AC) (doi:10.5067/GNSS/gnss_igsorb_001)
- SINEX files with combined IGS analysis centers (Associate Analysis Center, AAC) and regional combined SINEX files (Regional Network Associate Analysis Center, RNAAC); available through the CDDIS GNSS Station Position Products page

Other data products used:

- Interferometric Synthetic Aperture Radar (InSAR) deformation maps; available through NASA's Alaska Satellite Facility DAAC (ASF DAAC)

(Continued)

- Imagery created from data acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra and Aqua satellites; available for interactive exploration using the NASA Worldview data visualization application
- Meteorological products from the Technical University of Vienna; Vienna Mapping Functions (VMF) products (doi:10.17616/R3RD2H)
- GPS/GNSS RINEX data from multiple archives around the world

Read about the research:

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Herring, T.A., Melbourne, T.I, Murray, M.H., Floyd, M.A., Szeliga, W.M., King, R.W., Phillips, D.A., Puskas, C.M., Santillan, M. & Wang, L. (2016). "Plate Boundary Observatory and Related Networks: GPS Data Analysis Methods and Geodetic Products." *Reviews of Geophysics*, 54(4): 759-808 [doi:10.1002/2016RG000529].

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Ji, K.H. & **Herring, T.A.** (2012). "Correlation between changes in groundwater levels and surface deformation from GPS measurements in the San Gabriel Valley, California." *Geophysical Research Letters*, 39(1) [doi:10.1029/2011GL050195].

Published January 7, 2021

Who Uses Earth Science Data?

For the people of Asia and Southeast Asia, water is integral to their livelihood. Dr. Hossain uses NASA Earth observing data to improve water management and accelerate economic development in these regions.

Dr. Faisal Hossain in his University of Washington office. Screenshot from the SASWE video "Cotton Fields from the Ivory Tower," available at https://youtu.be/IlZctBnv8sM. Video copyright 2017 by Dr. Hossain and the University of Washington.

Dr. Faisal Hossain

Professor, Department of Civil and Environmental Engineering, University of Washington, Seattle, WA

Research interests: Using remotely-sensed data to address challenges of limited water, food, and energy resources in South and Southeast Asia with the overall goal of accelerating economic development in these regions.

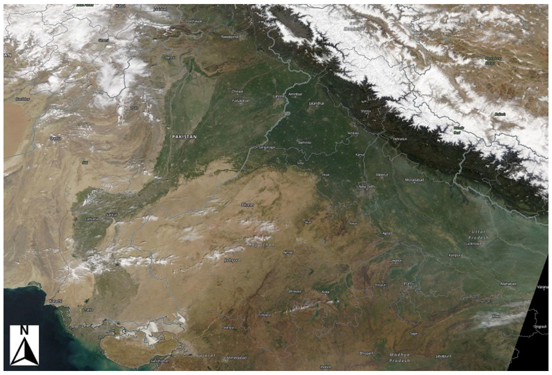
Research highlights: The Indus River begins its journey to the sea on a glacier near a sacred Tibetan mountain that is not to be climbed. The trickle of melting snow and glacial ice broadens and picks up speed as it flows northwestward through Tibet and into India, where it forms the westernmost river system in the Indian Subcontinent. The river turns south, and its path through Pakistan can easily be traced as a dark, greenish strip running the length of the country until it finally transitions into a broad delta where it empties into the Arabian Sea.

The Indus River basin spans more than one million square kilometers, and crosses the borders of China, India, Afghanistan, and Pakistan. For Dr. Faisal Hossain, the importance of the Indus River is not just the four countries it touches, but the approximately 300 million lives it touches. Having been born and spent part of his childhood in Southeast Asia, another vast region heavily dependent on water resources, Dr. Hossain experienced firsthand how a lack of information about water resources and a lack of access to Earth science data can make a country less resilient to natural or human-created vulnerabilities.

Now, as a professor of civil and environmental engineering at the University of Washington, he uses remotely-sensed Earth observing data as an integral resource in his work helping developing nations in South and Southeast Asia address challenges of limited water, food, and energy against a backdrop of accelerated economic development. Dr. Hossain uses satellite data from numerous NASA and international missions in his work. Data from many of these missions are freely available through NASA's Earth Observing System Data and Information System (EOSDIS), particularly NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC), which archives and distributes EOSDIS hydrologic data along with physical oceanographic data.

Dr. Hossain's projects are undertaken primarily through his Sustainability, Satellites, Water, and Environment Research Group (SASWE), which is located at the University of Washington. These projects are designed to foster better, more efficient use of water resources that can help improve the livelihoods of people dependent on freshwater systems across Asia. For work across such a broad swath of Earth, the spatial range of satellite data is an invaluable resource.

The Indus basin is a key example of a developing area experiencing the challenges Dr. Hossain and his colleagues are working to address. According to the United Nations



Terra MODIS corrected reflectance (True Color) image of the Indus River basin acquired March 23, 2020. The path of the Indus River through India and Pakistan can easily be traced as a darker, greenish swath. Interactively explore this image using NASA Worldview: https://go.nasa.gov/3bO3qzn. NASA Worldview image.

(Continued)

Office for Disaster Risk Reduction (UNDRR), the region is one of the most important river basins in the world in terms of human dependence, with a high population density relying on the river's water for uses including drinking, agriculture, and hydroelectric power. The resources provided by the river play a vital role in the economic development and environmental health of the region, but, as noted by the World Bank, population growth, urbanization, and climate change are exacerbating the basin's already stressed natural resources.

As Dr. Hossain observes, Pakistan is a country that does not have a comprehensive *in situ* groundwater monitoring network. Using water mass data acquired from the joint NASA/German Aerospace Center (DLR) Gravity Recovery and Climate Experiment (GRACE, operational 2002 to 2017), Dr. Hossain and his research group developed techniques to help the government of Pakistan overcome costly groundwater management challenges in an area impacting more than 100 million residents. The project team plans to use similar water mass data from the joint NASA/German Research Centre for Geosciences (GFZ) GRACE-Follow On (GRACE-FO) mission (launched in 2017) to further improve irrigation efficiency for growing staple crops like rice and wheat.

In another project in Pakistan, Dr. Hossain and his group used data from the joint NASA/Japan Aerospace Exploration Agency (JAXA) Global Precipitation Measurement Core Observatory (GPM, launched in 2014), the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Aqua satellite (launched in 2002), and instruments aboard the joint NASA/USGS Landsat series of satellites to develop a satellite-based irrigation advisory text messaging system designed to conserve water and improve crop yield. From an initial pilot-scale test involving 700 farmers, the success of this system enabled its expansion to 10,000 farmers in early 2017 and to 100,000 farmers in 2018. Through the application of satellite data and numerical weather models, crop water demand is now estimated for all of Pakistan using evapotranspiration estimation methods at nowcast and forecast scales that are available to farmers through text messaging.

For farmers receiving these irrigation advisories, this system has helped conserve approximately 2.5 cubic kilometers of groundwater per 100,000 farmers per year, and has doubled the annual income of farmers receiving these alerts through increases in crop yield. With the anticipated integration of GRACE and GRACE-FO data to detect regions where groundwater is being rapidly depleted, Dr. Hossain plans to increase the efficiency of the advisory system by providing targeted alerts to individual farmers in areas facing greater groundwater shortages.

Dr. Hossain (center, black jacket) with farmers in Bangladesh in 2018. The farmers' company worked with Dr. Hossain to have satellite data, weather forecasts, and agricultural advisories provided on the farmers' cellphones. Image courtesy of Dr. Hossain/University of Washington.

The success of the satellite-based irrigation advisory system in Pakistan enabled its expansion to roughly 1,000 farmers in India and 150 farmers in Bangladesh. Evaluations of the impact of these pilot systems reveal tremendous savings of irrigation water in Northern India along with increases in wheat yield.

Dr. Hossain's applied research using precipitation data from GPM and altimeter data from the joint NASA/French Space Agency (CNES) Ocean Surface Topography Mission (OSTM)/Jason-2 and Jason-3 missions contributed to the development of a flood forecasting system that is currently serving over 80 million people

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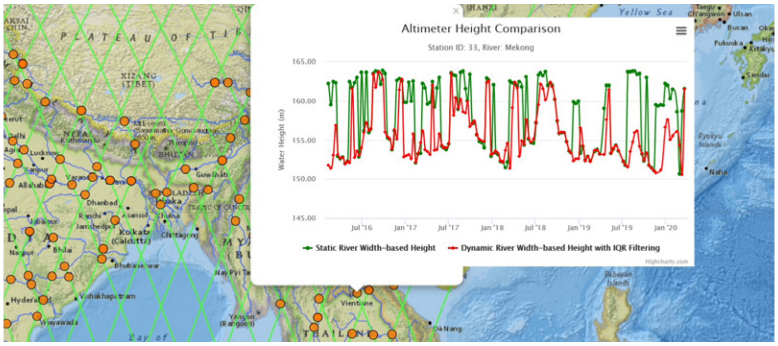
in Bangladesh. Recently, this forecasting scheme evolved to one based on global numerical weather prediction (NWP) forecasts using the NOAA Global Forecast System. Dr. Hossain's group developed an improved forecasting technique that can save approximately 5 to 10 hours each day of computer processing time while extending flood lead time by an extra five days.

In Southeast Asia, Dr. Hossain and his colleagues have applied their work using satellite-based observations to improving water management along the Mekong River. The Mekong River basin supports the livelihood of more than 60 million people as it flows through China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. The many dams and reservoirs along the river create a myriad of socio-environmental challenges. While these reservoirs and dams provide hydropower generation, flood control, irrigation, and water supply, Dr. Hossain points out that they also alter river flow, contribute to thermal pollution, and limit the transport of sediments, nutrients, and biota.



Screenshot of the SASWE Dynamic River Width based Altimeter Height Visualizer application co-created by Dr. Hossain. Green line is static river height based only on near real-time Jason-3 altimeter data; red line is river height inferred by combining Jason-3 with near real-time Sentinel-1 synthetic aperture radar (SAR) imagery to identify the width and location of the dynamic river. For more information about this application please see Biswas, N., et al. (2019), doi:10.1016/j.rse.2018.10.033.

In a recent research project partially supported by a NASA Applied Sciences grant, Dr. Hossain and his colleague, Dr. Matthew Bonnema, combined satellite observations with physical models using satellite-based data to infer the residence time of water in non-gauged reservoirs along the Mekong River. The research team defines *residence time* as a measure of the time delay between when water enters a reservoir and when it is released by human operating decisions. The team used a combination of satellite-derived radar altimetry-based water surface elevations from the OSTM/Jason-2 satellite and spectral (visible) band-based water surface area data acquired from instruments aboard the Landsat series of satellites. Dr. Hossain and Dr. Bonnema conclude that remotely-sensed satellite data can help the science community better understand the potential impacts of extensive reservoir construction in the developing world, where accurate gauging stations may be limited. This, in turn, will help improve water management, planning decisions, and reservoir operations for stakeholders of the basin.

Meanwhile, snow still falls near the sacred mountain in Tibet that is not to be climbed, and slowly makes its way to the sea. Through the use of NASA Earth observing data, Dr. Hossain and his colleagues are helping ensure that the economic, social, and environmental benefits to the people dependent on this water will continue to increase.

Representative data products used:

■ Available through PO.DAAC:

- JPL GRACE/GRACE-FO Gridded-AOD1B Water-Equivalent-Thickness Surface-Mass Anomaly RL06 dataset for Tellus Level-3 1.0-degree grid (short name: GRC-GFO_GRIDDED_AOD1B_JPL_1-DEG_RL06; doi: 10.5067/GGAOD-3GJ60)
- OSTM/Jason-2 and Jason-3, various altimetry data products

(Continued)

- MODIS Land Cover Type (MCD12Q1; doi: 10.5067/MODIS/MCD12Q1.006); available through NASA's Land Processes DAAC (LP DAAC)
- GPM Integrated Multi-satellitE Retrievals for GPM (IMERG) data; available through NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC)
- Sentinel-1 synthetic aperture radar (SAR) imagery; available through NASA's Alaska Satellite Facility DAAC (ASF DAAC); *NASA's provision of the complete European Space Agency (ESA) Sentinel-1 SAR data archive through the ASF DAAC is by agreement between the U.S. State Department and the European Commission (EC)*
- Landsat Thermal Infrared Sensor (TIRS) and visible data; available through the USGS EarthExplorer online search, discovery, and ordering tool

Read about the work and research:

Ahmad, S.K. & **Hossain, F.** (2020). "Maximizing Energy Production from Hydropower Dams using Short-Term Weather Forecasts." *Renewable Energy,* 146: 1560-1577 [doi: 10.1016/j.renene.2019.07.126].

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Published April 30, 2020

Who Uses Earth Science Data?

Coastal ecosystems are some of Earth's most biologically diverse environments, especially coastal mangrove forests. Dr. Lagomasino uses Earth observing data to study these vital biomes.

Dr. Lagomasino (front, in hat) and students from Omar Bongo University at Pongara National Park in the West African nation of Gabon. Directly behind Dr. Lagomasino are his colleagues Dr. Chris Beirne (University of British Columbia-Vancouver; center left) and Dr. Michael Denbina (NASA's Jet Propulsion Laboratory; center right in hat). Image courtesy of Dr. Lagomasino.

Dr. David Lagomasino

Assistant Professor, Department of Coastal Studies, East Carolina University, Greenville, NC; Research Scientist, East Carolina University Coastal Studies Institute, Wanchese, NC

Research Interests: Dr. Lagomasino uses a combination of field data, environmental data, and remotely-sensed observations to study the impacts of human and natural disturbances on coastal ecosystems and the responses of the coastal landscape (both on land and under the sea) to these pressures.

Research Highlights: Vegetation living in coastal environments face a never-ending struggle of surviving highly saline water, constantly shifting sediments, and periodic destructive storms. That mangroves thrive in these conditions is a testament to not only their adaptability, but also their sheer resiliency.

Comprising shrubs or trees that grow in coastal saline or brackish water, coastal mangrove forests occupy a relatively small global ecological footprint. However, these biomes are some of the most ecologically diverse areas on Earth and the foundation of the coastal food web. As scientists like Dr. David Lagomasino are quick to point out, mangrove forests are important ecosystems for maintaining the planet's health through their work as carbon sinks.

Dr. Lagomasino's research focus is on coastal ecosystems and global coastline change, and mangrove forests figure prominently in his work. Understanding the structure and function of coastal systems is critical for determining their health and development. Remotely-sensed data products that are freely available through NASA's Earth Observing System Data and Information System (EOSDIS) help enable him to conduct research on a global scale.

A principal EOSDIS source for Dr. Lagomasino's data is NASA's Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). A partnership between NASA and the U.S. Department of Energy, ORNL DAAC is responsible for EOSDIS data related to biogeochemical dynamics, ecology, and environmental processes.

In particular, Dr. Lagomasino relies on ORNL DAAC-distributed datasets that are part of the NASA Carbon Monitoring System (CMS). This is not surprising since mangrove forests are one of the most carbon-dense ecosystems in the world and, as noted by the Smithsonian Institution, a critical component in mitigating climate change. According to a recent study, global mangrove forests are estimated to contain as much as 6.4 petagrams of carbon (PgC) in the top meter of soil (for perspective, one petagram is equal to one billion metric tons). As Dr. Lagomasino observes, the loss of coastal wetlands has the potential to release high concentrations of carbon dioxide (CO_2) through the loss of soils. In fact, the above-mentioned study attributes the loss of mangrove forests between 2000 and 2015 to the release of up to 122 million tons of carbon as the soils and biomass in which this carbon was stored were disturbed or destroyed.

Using remotely-sensed data from a number of satellite-borne instruments, Dr. Lagomasino was the lead author on a CMS dataset providing estimates of mangrove extent for 2016 and mangrove change (gain or loss) from 2000 to 2016 in major river delta regions of six countries: Gabon, Jamaica, Mozambique, Peru, Senegal, and Tanzania. The *Mangrove Forest Cover Extent and Change across Major River Deltas, 2000-2016,* dataset (doi: 10.3334/ORNLDAAC/1670) is available through ORNL DAAC.

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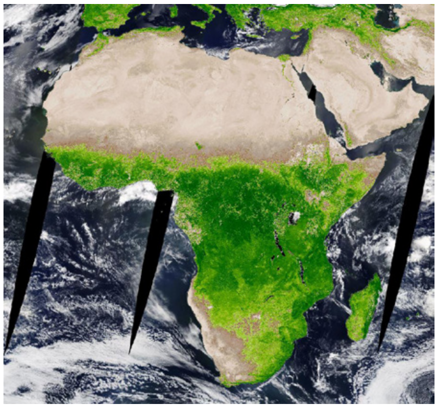
While mangrove forest habitat loss can be due to human factors, such as water diversion, deforestation, and the destruction of mangroves for the development of shrimp farms, natural disasters also take a toll on these vital ecosystems. During tropical storms, coastal mangroves help buffer inland communities from strong winds and storm surges. However, mangroves can be severely damaged by these storms even as they help alleviate their impact.

The extremely strong 2017 Atlantic hurricane season, for example, caused tremendous damage to mangrove forests across the Caribbean. Dr. Lagomasino was part of a research team that used a combination of remotely-sensed data from multiple platforms to examine the effects of these storms on mangrove forest degradation and canopy structure.

An important sensor-derived measurement used by the research team to assess mangrove health was the Normalized Difference Vegetation Index, or NDVI. NDVI is calculated from the difference between visible and near-infrared light reflected by vegetation. Healthy vegetation absorbs most of the visible light that hits it and reflects a large portion of light in near-infrared wavelengths. Unhealthy or sparse vegetation absorbs more near-infrared light and reflects more light in the visible spectrum. These differences in reflectance can easily be detected by multispectral instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra and Aqua satellites or the Enhanced Thematic Mapper+ (ETM+) and Operational Land Imager (OLI) instruments aboard the joint NASA/USGS Landsat series of satellites.



NASA Terra MODIS NDVI image of Africa and the Middle East from May 22, 2020. NDVI values range from -0.2 to 1. Higher values (0.3 to 1, shown in shades of green) indicate areas covered by green, leafy vegetation. Values lower than 0.3 (shown in shades of tan or brown) indicate areas where there is little or no vegetation. Interactively explore this image using NASA Worldview: https://go.nasa.gov/2ZRF8RY. NASA Worldview image.

Based on NDVI data, Dr. Lagomasino and his colleagues found that 30 times more mangrove areas were damaged in 2017 than in the previous eight hurricane seasons. NDVI data also indicated that a majority of this vegetation damage persisted for at least seven months after the end of the hurricane season.

To determine mangrove canopy height during the study, Dr. Lagomasino and his colleagues used high-resolution airborne lidar data. Lidar, an acronym for *light detection and ranging,* is a remote-sensing technique that uses laser pulses to precisely map ground elevation. The research team relied on data collected from a NASA airborne system called Goddard's Lidar, Hyperspectral & Thermal Imager (G-LiHT). G-LiHT collects multiple measurements simultaneously, including lidar-derived vegetation height and high-resolution photographs.

Following Hurricane Irma (August 30 to September 12, 2017), Dr. Lagomasino was part of a team of researchers from NASA's Goddard Space Flight Center in Greenbelt, MD, Florida International University, the University of Maryland, and Everglades National Park that examined the extent of mangrove mortality in the Florida Keys and Everglades National Park. Using pre- and post-hurricane G-LiHT and NDVI data combined with satellite imagery, the team was able to build predictive models of the research area to assess the change in vegetation over time.

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G-LiHT images showing impacts to mangrove communities in Ten Thousand Islands in the Florida Everglades. ***Left image*** was acquired before Hurricane Irma, and shows a majority of healthy green vegetation. ***Right image*** was acquired after Hurricane Irma and shows significantly less green, healthy vegetation. NASA images.

The team used two primary assessments. G-LiHT lidar data were analyzed for changes in forest structure, while re-greening of vegetation was analyzed using Landsat imagery acquired every 16 days after Irma. The areas that received damage and that did not re-green were considered the most impacted, and covered a significant portion of the forest. As Dr. Lagomasino points out, though, areas that did not re-green following the hurricane may not have been healthy to begin with.

Along with being included in airborne systems like G-LiHT, lidar also is carried aboard satellites. The Advanced Topographic Laser Altimeter System (ATLAS) lidar aboard NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) spacecraft (launched in September 2018) fires 10,000 laser pulses per second to precisely map Earth's elevation (compared with 40 pulses per second in the original ICESat laser). About 20 trillion photons leave ATLAS with each pulse and about a dozen photons make the 3.3 millisecond return trip for detection by the satellite's 2.6-foot diameter beryllium telescope. When this travel time is combined with the satellite's GPS and star trackers, ICESat-2 can measure surface height to a precision of about one inch (about the length of a standard paperclip).

In an ongoing NASA-funded research project, Dr. Lagomasino is part of a multi-national team using ICESat-2 ATLAS data to estimate mangrove canopy height and tidal levels in coastal wetlands, provide shallow water bathymetry data for seagrass and coral reef mapping, and produce maps of coastal zone ecosystem structure. The project is examining coastal ecosystems around the world, including in the Gulf of Mexico, the Caribbean, Ecuador, Venezuela, Columbia, French Guyana, Mozambique, and Tanzania.

As Dr. Lagomasino's research shows, the damage to coastal mangrove ecosystems from both human and environmental impacts has implications far beyond the limited ecological extent of these areas. From assessing vegetative health to tracking the tremendous amounts of carbon released as these vital ecosystems are damaged or degraded, sensors aboard Earth observing satellites are providing the spatial and temporal data that help enable his studies.

Representative data products used:

- Data available through ORNL DAAC:
  - NASA Carbon Monitoring System (CMS) data:
    - Mangrove Forest Cover Extent and Change across Major River Deltas, 2000-2016; dataset co-developed by Dr. Lagomasino (doi: 10.3334/ORNLDAAC/1670)
    - Global Mangrove Distribution, Aboveground Biomass, and Canopy Height (doi: 10.3334/ORNLDAAC/1665)

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- Aboveground Biomass, Landcover, and Degradation, Kalimantan Forests, Indonesia, 2014 (doi: 10.3334/ORNLDAAC/1645)
- Lidar-derived Canopy Height, Elevation for Sites in Kalimantan, Indonesia, 2014 (doi: 10.3334/ORNLDAAC/1540)
- Estimated Deforested Area Biomass, Tropical America, Africa, and Asia, 2000 (doi: 10.3334/ORNLDAAC/1337)

- ATLAS/ICESat-2 L3A Land and Vegetation Height, Version 2 (ATL-08; doi: 10.5067/ATLAS/ATL08.002); available through NASA's National Snow and Ice Data Center DAAC (NSIDC DAAC) (*Version 3 of this dataset is available: doi: 10.5067/ATLAS/ATL08.003*)
- G-LiHT data; available using the G-LiHT Data Center Web Map
- Datasets available through the United Nations Environment Program (UNEP) World Conservation Monitoring Center (WCMC):
  - Global Mangrove Watch (GMW); Dataset ID: GMW-001
  - Global Distribution of Mangroves; Dataset ID: WCMC-010

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Who Uses Earth Science Data?

Global climate change is leading to shifts in vital ecosystems. Dr. Malone uses Earth observation data to explore how a changing climate impacts ecosystem structure and function.

Dr. Sparkle Malone

Assistant Professor, Department of Biological Science, Florida International University, Miami, FL

Research interests: Dr. Malone uses remotely-sensed data, eddy covariance, and model simulations to study how a changing climate and disturbances influence ecosystem structure and function.

Research highlights: If Dr. Sparkle Malone leaves her office at Miami's Florida International University by the north gate, she can travel in one of two directions on U.S. Highway 41. A right turn takes her east on a short drive to the skyscrapers surrounding the most populous city in Florida. During 2016, Miami released approximately 1,210,811 metric tons of carbon dioxide equivalents (CO_2e) community-wide, according to figures available from Miami Beach Rising Above, a website providing information about Miami's climate control and sustainability efforts. The website notes that this amount is equivalent to the emissions from more than 250,000 passenger vehicles driven for one year.

If Dr. Malone turns left on Highway 41, though, heading west across the Ronald Reagan Turnpike and Krome Avenue, she soon finds herself in one of the planet's most ecologically diverse areas – the Florida Everglades. Recent research indicates that mangrove forests in the Everglades store carbon worth between $2 billion and $3.4 billion, a value that reflects the estimated cost of restoring freshwater flow to preserve the mangroves. The ability of the 1.5-million-acre Everglades ecosystem to act as a carbon sink and prevent the release of carbon into the atmosphere figures prominently in not only Dr. Malone's research, but also in a changing global climate.

Through the use of models, field observations, and remotely-sensed data, including data from NASA's Earth Observing System Data and Information System (EOSDIS), Dr. Malone investigates how disturbances (both natural and human-caused) and changes in climate are leading to increases in atmospheric carbon dioxide (CO_2) or shifts in land cover type over time, both of which can be detected, measured, and tracked by sensors aboard Earth observing satellites.

A primary EOSDIS source for data used by Dr. Malone is NASA's Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). Located in Oak Ridge, TN, ORNL DAAC is a partnership between NASA and the U.S. Department of Energy. The DAAC archives and distributes EOSDIS data related to ecology, terrestrial biogeochemistry, and environmental processes.

Along with various datasets distributed by ORNL DAAC, Dr. Malone uses several resources available through the DAAC. These include the Moderate Resolution Imaging Specrtoradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) Land Products Global Subsetting and Visualization Tool (doi: 10.3334/ORNLDAAC/1379) and a system called Daymet. The subsetting and visualization tool provides selected MODIS/VIIRS land products that can be used for validating models and remote-sensing products as well as for characterizing field sites. Daymet provides near-surface meteorological information for remote areas or for areas with limited instrumentation throughout continental North America (along with Hawaii and Puerto Rico).

Dr. Malone also acquires EOSDIS data from NASA's Land Processes DAAC (LP DAAC). LP DAAC is a partnership between NASA and the USGS, and archives and distributes EOSDIS data related to land cover and land use, including MODIS land data products.

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In a recent study, Dr. Malone was part of a team investigating how increases in water level and periods of inundation contribute to changes in CO_2 storage in a freshwater wetland ecosystem in Everglades National Park. Between 2015 and 2017, a combination of higher than normal precipitation along with water management activities that altered the flow of freshwater in canals adjacent to the park led to an extended inundation period lasting almost 18 months. This unusually long period of inundation enabled the research team to test the ecosystem's response to abnormal inundation scenarios that may occur more frequently with climate change and the impact of this on carbon storage.

To assess the flow (or *fluxes*) of CO_2 in the study site, the team relied on eddy covariance measurements. Eddy covariance is a measure of the flow of trace gasses between ecosystems and the atmosphere, which can be assessed using sensors affixed to towers. These data are constantly being collected by global flux measurement sites that are integrated into a network called FLUXNET. Key attributes of the eddy covariance method noted on the FLUXNET website are its ability to measure fluxes directly in the field, at a spatial scale of hundreds of meters, and on time scales ranging from hours to decades. An eddy covariance tower installed in 2007 in the Everglades research site used by Dr. Malone and her colleagues provided nearly 10 years of CO_2 flux data for the study.

Dr. Malone standing in front of instruments comprising the newest eddy covariance tower site located just west of Everglades National Park in south Florida.

To explain the responses of CO_2 fluxes to inundation, the research team assessed the health of vegetation in the study area using a measurement called the Normalized Difference Vegetation Index (NDVI). NDVI is calculated from the difference between visible and near-infrared light reflected by vegetation. Healthy vegetation absorbs most of the visible light that hits it and reflects a large portion of light in near-infrared wavelengths; unhealthy or sparse vegetation absorbs more near-infrared light and reflects more light in the visible spectrum. These differences can be detected by multi-spectral sensors aboard Earth observing satellites, such as the MODIS instrument aboard NASA's Terra (launched in 1999) and Aqua (launched in 2002) satellites. Healthy vegetation is able to trap and hold carbon; unhealthy, stressed, or inundated vegetation can release carbon and act as a carbon source.

Dr. Malone and her colleagues found that the intensive inundation events between 2015 and 2017 were able to eventually turn the study-site ecosystem from a CO_2 sink into a CO_2 source. The team further notes that other freshwater wetlands that have regular inundation periods may exhibit similar responses depending on the inundation tolerance of the dominant plant species. One conclusion by the team is that extreme flooding due to climate change or human water management activities may change the vital role of wetlands as carbon sinks.

Dr. Malone hiking through a grassland in Wayqecha, Peru, in 2020 as part of her current research exploring the role of frogs on soil carbon respiration in grasslands and forests.

Dr. Malone's research is not just confined to carbon fluxes in wetlands. She has undertaken numerous studies on the effects of wildland fire, drought, and other disturbances on ecosystems in the Everglades and in western states including Colorado and California. Through the use of remotely-sensed data, including data in the

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EOSDIS collection, Dr. Malone continues her research connecting the dots between ecosystem disturbance and the effects of this on ecosystem structure and function in a changing global climate.

Representative data products and tools used:

- Available through ORNL DAAC:
  - MODIS and VIIRS Land Products Global Subsetting and Visualization Tool (doi: 10.3334/ORNLDAAC/1379)
  - Daymet Daily Surface Weather Data (doi: 10.3334/ORNLDAAC/1328)
  - Arctic-Boreal Vulnerability Experiment (ABoVE): Landsat-derived Burn Scar differenced Normalized Burned Ratio (dNBR) across Alaska and Canada, 1985-2015 (doi: 10.3334/ORNLDAAC/1564)
- MODIS data products available through LP DAAC:
  - Terra/Aqua Leaf Area Index/Fraction of Photosynthetically Active Radiation (FPAR) (MCD15A2H v006; doi: 10.5067/MODIS/MCD15A2H.006)
  - Terra/Aqua Land Cover Type (MCD12Q1 v006; doi: 10.5067/MODIS/MCD12Q1.006)
  - Terra Net Evapotranspiration (MOD16A2 v006; doi: 10.5067/MODIS/MOD16A2.006)
  - Terra Vegetation Indices (MOD13Q1 v006; doi: 10.5067/MODIS/MOD13Q1.006)
  - Terra Gross Primary Productivity (MOD17A2HGF v006; doi: 10.5067/MODIS/MOD17A2HGF.006)
  - Terra Net Primary Production (MOD17A3HGF v006; doi: 10.5067/MODIS/MOD17A3HGF.006)
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) 1 arc second (ASTGTM v003; doi: 10.5067/ASTER/ASTGTM.003); available through LP DAAC
- AmeriFlux data; available through the AmeriFlux website
- Imagery from the National Aerial Photography Program (NAPP; doi: 10.5066/F7VD6WQZ); available through the USGS EarthExplorer online search, discovery, and ordering tool

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Published August 3, 2020

Who Uses Earth Science Data?

Aerosols have a huge impact on climate and human health. Dr. Steven Massie uses remotely-sensed data to better understand these impacts and improve how aerosols are detected by Earth observing satellites.

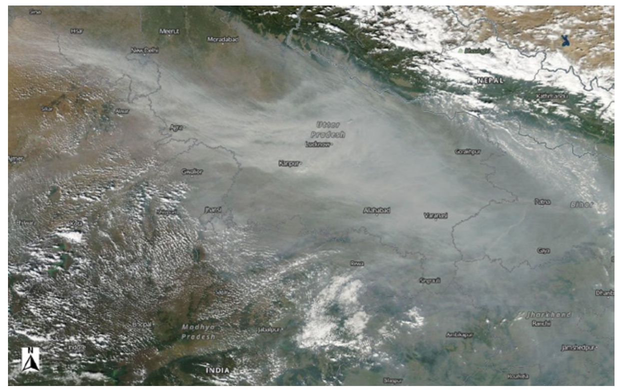
Dr. Steven Massie

Research Associate, Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado, Boulder, CO

Research interests: Effects of aerosols and clouds on the interpretation of NASA satellite data and the physical effects of aerosols on the troposphere.

Research highlights: As the song says, on a clear day, you can see forever. That is, of course, unless microscopic suspended particles in the atmosphere, called *aerosols,* restrict visibility. While atmospheric aerosols occur naturally from a wide range of sources, including ash from volcanic eruptions and smoke from wildland fires, human activity has significantly increased their concentrations. This is easily seen in photographs of cities like Beijing, China, and New Delhi, India, where a gray to yellow cloud turns an otherwise clear day into a twilight of fog.

Haze and reduced visibility caused by atmospheric aerosols are not only visible on the ground. High aerosol concentrations also can be observed and tracked from space using instruments aboard Earth observing satellites. NASA has collected data on atmospheric aerosols for more than 40 years, about the same amount of time Dr. Steven Massie has used these data to analyze and study the impacts of aerosols on the lower atmosphere and explore ways these particles can be better detected by satellite-borne instruments.



Smoke and other aerosols are clearly seen as a milky-white layer in this Aqua/MODIS image of Northern India acquired on November 4, 2019. These aerosols are primarily smoke from agricultural burning, and contrast with bright white clouds to the south. Interactively explore this image using NASA Worldview at https://go.nasa.gov/37Zlwwj. NASA Worldview image.

The atmospheric data used by Dr. Massie are part of NASA's Earth Observing System Data and Information System (EOSDIS) collection, and are available through several EOSDIS Distributed Active Archive Centers (DAACs). The primary DAAC through which Dr. Massie acquires the data he uses in his current research is NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC), which archives and distributes EOSDIS data related to atmospheric composition and atmospheric dynamics, global precipitation, and solar irradiance. Other EOSDIS DAACs with collections of aerosol data include NASA's Atmospheric Science Data Center (ASDC) and NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS DAAC).

Aerosols directly impact the lowest level of Earth's atmosphere, called the *troposphere*, which extends from Earth's surface to an average altitude of 10 km (about 33,000 feet). As Dr. Massie notes, aerosols in the troposphere can have both a warming and a cooling effect. Aerosols comprising desert dust and carbon-based soot (such as from agricultural burning) absorb and trap radiation in the atmosphere, which prevents heat from escaping into space and contributes to atmospheric warming. Conversely, suspended aerosols also can scatter a fraction of incoming solar radiation back to space, which leads to atmospheric cooling. In addition, aerosols also serve as condensation nuclei for raindrop formation and can lead to

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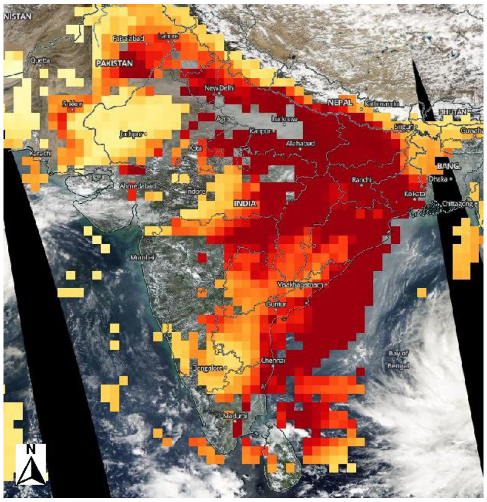
a higher amount of smaller cloud droplets. This higher number of cloud droplets can result in more extensive areas of clouds that can reflect radiation back into space and further contribute to atmospheric cooling.

Atmospheric aerosols also impact human health. Aerosols with a diameter less than 2.5 micrometers (µm) – which is about 30 times smaller than a human hair – are easily inhaled and can penetrate deep into the lungs (and even into the bloodstream). According to the U.S. Environmental Protection Agency (EPA), concentrations of 2.5 µm particulate matter (notated $PM_{2.5}$) above 35 micrograms per cubic meter (µg/m^3) over a 24-hour period are considered unhealthy. While a clear, non-hazy day can have $PM_{2.5}$ concentrations as low as 5 µg/m^3, cities such as New Delhi, India, and Cairo, Egypt, have average annual $PM_{2.5}$ concentrations of more than 140 µg/m^3 and 110 µg/m^3, respectively, based on World Health Organization (WHO) Global Ambient Air Pollution data.

One key measurement of aerosols collected by Earth observing satellites is aerosol optical depth (AOD). AOD is a measure of the amount of light absorbed and scattered by atmospheric aerosols. An optical depth of less than 0.1 indicates a clear sky with maximum visibility; values of 1.0 or higher indicate the presence of aerosols so dense that people would have difficulty seeing the Sun and could experience health impacts. AOD can be explored globally using the NASA Worldview data visualization application.



Aqua/MODIS AOD over India for November 4, 2019 (the same date as the above image). Dark red areas in eastern India indicate AOD values as high as 2.0. NASA Worldview image.

NASA has collected aerosol and AOD data using a number of satellite-borne instruments. In a study looking at aerosol concentrations over Asia between 1979 and 2000, Dr. Massie and his colleagues used 20 years of AOD data acquired by NASA's Total Ozone Mapping Spectrometer (TOMS) instrument. TOMS flew aboard several NASA and international satellite missions starting with NASA's Nimbus-7 mission in 1978. The research team specifically looked at TOMS AOD data collected between November and February – months during the Northern Hemisphere winter in which the influences of desert dust and smoke from fires in Asia are generally less than in other months. As noted by Dr. Massie and his colleagues, the populations of China and India increased 26% and 23% per decade, respectively, between 1979 and 2000, with accompanying increases in coal, oil, biomass consumption, and land-altering activities. During this time, TOMS AOD data show that aerosol concentrations increased by 17% per decade and sulfur dioxide (SO_2) emissions increased by 35% per decade during winter over the China coastal plain.

Dr. Massie's current research uses data from NASA's Orbiting Carbon Observatory-2 (OCO-2) mission (operational 2014 to present). OCO-2's primary science objective is to collect measurements of atmospheric carbon dioxide (CO_2) and quantify the variability of CO_2 over seasonal cycles. OCO-2 provides roughly 100,000 global CO_2 measurements every day. OCO-2's data record continues with data from OCO-3, which was installed on the International Space Station on May 6, 2019, and began science operations on June 25, 2019. Data from both OCO-2 and OCO-3 are available through GES DISC. While OCO-2 circles Earth in a 705-km polar orbit,

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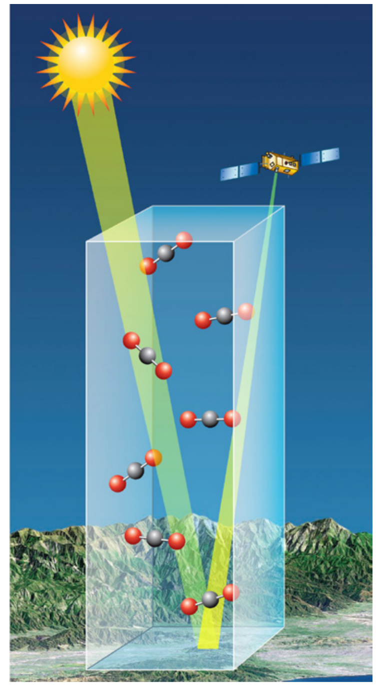
the space station orbits Earth between 52 degrees north and south latitude at an altitude ranging from 330 to 435 km. This lower orbit enables OCO-3 to collect denser data than OCO-2 over high-carbon regions, such as the Amazon and most major global cities.

OCO-2 measures CO_2 indirectly by measuring the intensity of sunlight reflected by molecules of CO_2 in a column of air. Atmospheric CO_2 absorbs light energy at specific wavelengths, and the OCO-2 instrument uses a diffraction grating (like the back of a compact disk) to separate incoming sunlight into a spectrum of multiple component colors. OCO-2 CO_2 measurements are based on the number of molecules of CO_2 per cubic meter. When CO_2 is measured, the quantity that is being determined is the "mole fraction" of CO_2 in a column of air. This is the number of CO_2 molecules in a column of air after removal of water vapor, and is designated X_{CO2}.


Sunlight rays entering the OCO-2 instrument pass through the atmosphere twice: once as they travel from the Sun to Earth and then again as they bounce off Earth's surface to the instrument for detection. NASA JPL/Caltech illustration.

While this measurement strategy works fine in clear air, OCO-2 measurements can be biased by clouds within and outside the instrument's field of view. The shapes, altitudes, and even colors of clouds constantly change. This, in turn, continually changes the amount of cloud-reflected light that is received by the OCO-2 instrument. As a result, methods for screening out cloud-influenced measurements are a focus of OCO-2 algorithm developers.

In a recent research project, Dr. Massie was part of a team that used OCO-2 data along with data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) instrument to examine biases caused by clouds in the retrieval of OCO-2 data. Observing that the OCO-2 objective is to measure CO_2 to better than 1% accuracy on regional scales (defined on the OCO-2 website as 1,000 kilometers or greater), Dr. Massie and his colleagues analyzed OCO-2 CO_2 measurements and MODIS satellite radiance and cloud fields. The team found that as cloud fields become less uniform and more spatially heterogeneous, cloud-reflected light causes greater variations of OCO-2 CO_2 measurements at local scales, which the research team defines as 20 km×20 km. Based on the results of this research, Dr. Massie and his colleagues recommend that OCO-2 data algorithm development should incorporate techniques designed to deal with instances when cloud fields are not uniform and light is not reflected evenly to help deal with these potential biases in CO_2 retrievals.

Thanks to research by Dr. Massie and his colleagues, our ability to retrieve and utilize accurate data about aerosols and clouds, along with our ability to better understand their impacts on Earth's troposphere, continues to improve. This, in turn, is leading to better data to help develop more informed policies to deal with the effects of aerosols.

Representative data products used:

- OCO-2 data products available through GES DISC:
  - Calibrated Spectra:
    - OCO-2 Level 1B calibrated, geolocated science spectra, Retrospective Processing V8r (doi: 10.5067/1RJW1YMLW2F0)

(Continued)

- Retrievals of CO_2:
  - OCO-2 Level 2 bias-corrected X_{CO2} and other select fields from the full-physics retrieval aggregated as daily files, Retrospective processing V9r (doi: 10.5067/W8QGIYNKS3JC)
- MODIS data products available through GES DISC:
  - MODIS Calibrated Radiances
  - MODIS Cloud Mask
- Geostationary Radiances from the Advanced Baseline Imager (ABI) aboard the joint NASA/NOAA Geostationary Operational Environmental Satellite-R Series (GOES-R) GOES-16 satellite; available through NOAA's Comprehensive Large Array-Data Stewardship System (CLASS)

Read about the research:

Massie, S.T., Sebastian Schmidt, K., Eldering, A. & Crisp, D. (2017). "Observational evidence of 3D cloud effects in OCO-2 CO_2 retrievals." *Journal of Geophysical Research: Atmospheres*, 122(13): 7064-7085 [doi: 10.1002/2016JD026111].

Massie, S.T., Gille, J, Craig, C., Khosravi, R., Barnett, J., Read, W. & Winker, D. (2010). "HIRDLS and CALIPSO observation of tropical cirrus." *Journal of Geophysical Research*, 115 [doi: 10.1029/2009JD012100].

Massie, S.T., Torres, O. & Smith, S.J. (2004). "Total Ozone Mapping Spectrometer (TOMS) observations of increases in Asian aerosol in winter from 1979 to 2000." *Journal of Geophysical Research*, 109(D18) [doi: 10.1029/2004JD004620].

Published January 30, 2020

Who Uses Earth Science Data?

Imagery of Earth at night provide unique opportunities for research. Dr. Miller uses these data in his studies of Earth's nocturnal environment.

Dr. Steven D. Miller

Senior Research Scientist,
Colorado State University;
Deputy Director, Cooperative Institute for Research in the Atmosphere (CIRA),
Fort Collins, CO

Research interests: Using remotely-sensed data, especially near real-time low-light observations, to observe and characterize components of Earth's weather and climate system at night.

Research highlights: *"... let him be called from his hammock to view his ship sailing through a midnight sea of milky whiteness . . ." – Herman Melville, Moby Dick.*

On a moonless night off the coast of Somalia in January, 1995, lookouts aboard the British merchant vessel *S.S. Lima* noticed an unusual brightening on the southern horizon. The sailors likened the eerie glow to an aurora borealis; but this glow was not coming from the sky. Slowly, silently, the ship moved across a sharp boundary between the dark sea and what was described as looking like a "field of snow" stretching from horizon to horizon. Nearly 150 years after Herman Melville's 19th century description, the *S.S. Lima* spent six hours crossing a glowing white sea with the appearance of milk. Sailors described the experience as "gliding over the clouds."

In 2005, while pondering the potential of a new generation of low-light satellite sensors, Dr. Steven Miller and his colleagues stumbled upon the account of the *S.S. Lima*. They used data from the Operational Linescan System (OLS) aboard the Defense Meteorological Satellite Program (DMSP) constellation of Earth observing satellites to spot a 15,400 km^2 swath of glowing water swirling counterclockwise within an ocean gyre. This Connecticut-sized feature was the first confirmed detection from space of the milky seas of maritime lore, and thought to be caused by a rare form of widespread bacterial bioluminescence.

The *science of the night*, as Dr. Miller describes it, is a principal focus of his research at the Cooperative Institute for Research in the Atmosphere (CIRA), which has operated as a formal partnership between NOAA and Colorado State University since 1980. Using data freely and openly available through NASA's Earth Observing System Data and Information System (EOSDIS), he seeks to gain insight into Earth processes using low-light visible measurements of the planet.

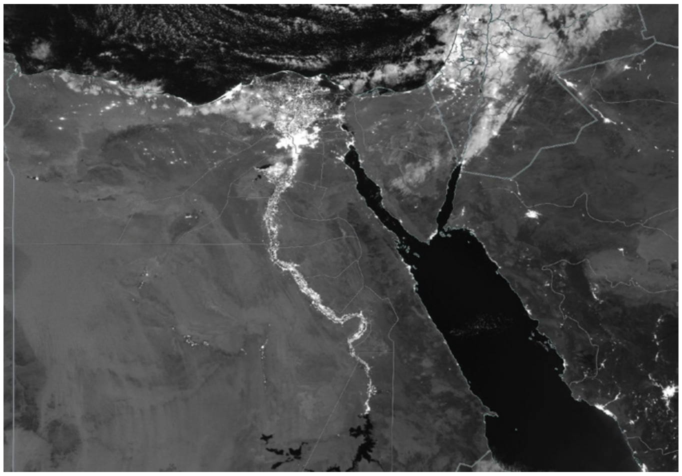
CIRA
Connecting Models and Observations

An important source of data for Dr. Miller's nighttime research is near real-time (NRT) imagery from NASA's Land, Atmosphere Near real-time Capability for EOS, or LANCE. LANCE produces more than 200 NRT data products from almost a dozen satellite instruments that generally are available within three hours of a satellite observation. While LANCE NRT data do not have the extensive processing required for scientific research, they are an invaluable resource for applications such as numerical weather and climate prediction, natural hazards monitoring, ecological/invasive species assessment, agriculture, air quality, disaster relief, and homeland security.

(Continued)

In particular, Dr. Miller uses LANCE data and imagery from the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership satellite (Suomi NPP, launched in 2011) and from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Terra (launched in 1999) and Aqua (launched in 2002) Earth observing satellites.

One key NRT data product used frequently by Dr. Miller is VIIRS Day/Night Band (DNB) imagery. DNB imagery is available from the VIIRS aboard Suomi NPP as well as from the VIIRS aboard the NOAA-20 satellite (launched in 2017). Both satellites operate as part of the collaborative NASA/NOAA Joint Polar Satellite System (JPSS).



Suomi NPP/VIIRS DNB image from November 4, 2020, showing the Nile River and Cairo in the center with Israel in the upper right. Interactively explore this image using NASA Worldview at https://go.nasa.gov/3p1r4zO.
NASA Worldview image.

The VIIRS DNB layer is designed to capture low-light emissions under a wide range of illumination conditions, displayable as a gray-scale image. Using the NASA Worldview data visualization application, DNB imagery is available from November 11, 2016, to present. As Dr. Miller observes, DNB imagery help fill temporal gaps where visible-light information is traditionally not available between sunset and sunrise. This imagery is particularly useful for high latitude studies and support of operational users during the polar winters.

NASA Worldview has proven to be a valuable resource in Dr. Miller's research as he canvasses the globe in search of phenomena detectable using VIIRS DNB imagery. These include surface features, such as lights from human sources, wildfires, and ocean bioluminescence; tropospheric features, such as clouds and aerosols; and middle-to-upper atmospheric features, such as auroras. Many of these phenomena are more readily seen by reflected moonlight, while others create light of their own. In a recent project, one of his student interns made extensive use of Worldview and the DNB imagery layer to compile an inventory and taxonomy record of atmospheric gravity waves.

Atmospheric gravity waves are one of the key forms of energy transfer between the lower and upper atmosphere, and drive important sub-seasonal to seasonal-scale circulation patterns that influence our weather as well as aspects of general circulation that define our climate. Created by a variety of mechanisms, including convective storms and flow over mountains, these waves are detectable using DNB imagery in a novel way. If upward-propagating gravity waves (such as those generated during a thunderstorm) reach the middle atmosphere – without breaking or being absorbed along the way – they will change the temperature and density structure of the atmosphere. The changes caused by gravity waves affect the brightness of an atmospheric region that produces visible light emissions as gas molecules become electrically excited. These light emissions are called *airglow.*

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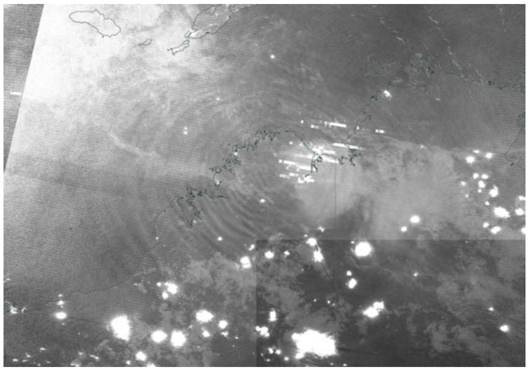
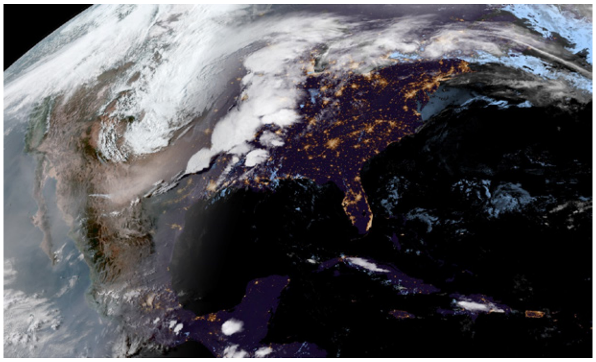
Nighttime airglow (or *nightglow*) regions occur primarily in two discrete layers of the atmosphere: a narrow (~10 km thick), stronger layer centered near 90 km above the surface and a broader (200 to 400 km), weaker emission layer centered near 250 km above the surface. Airglow produces faint light emissions in blue, green, red, and near-infrared spectral lines (according to the gaseous species involved). In DNB imagery, gravity waves passing through the nightglow layers appear as ripples of light. As Dr. Miller observes, "NASA Worldview is a great resource for observing these important forms of energy transfer in the atmosphere, which easily can be picked out visually in properly scaled DNB imagery on moonless nights."



Example of gravity waves in airglow over the northern coast of Australia on December 14, 2017, as seen in a Suomi NPP/VIIRS DNB image viewed using NASA Worldview. Gravity waves are seen as faint ripples radiating from the image center; white rectangular streaks atop the thunderstorm responsible for these waves is lightning. Explore this image in Worldview at https://go.nasa.gov/32vrwwy. NASA Worldview image.

Another area of Dr. Miller's research is designing algorithms that attempt to isolate and enhance key environmental features by way of their unique spatial, temporal, and spectral properties. These enhancements make it easier for analysts to identify specific features (such as snow, dust, or clouds) in a complex environmental scene. An example of this value-added imagery is *GeoColor*, a popular imagery product used by scientists, forecasters, and the media that is being produced semi-operationally by NOAA's National Environmental Satellite, Data, and Information Service (NESDIS).

Applied to the new generation of NOAA Geostationary Operational Environmental Satellites (GOES), GeoColor is the culmination of years of behind-the-scenes scientific research that includes atmospheric corrections, incorporation of DNB-observed city lights at night, and the design of a synthetic green band (whose development and proof-of-concept leveraged NASA's MODIS instruments on Terra and Aqua). A real-time global GeoColor animation is available on the Satellite Loop Interactive Data Explorer in Real-time (SLIDER) on the CIRA website and at NOAA's GOES Image Viewer.



GeoColor image acquired on April 14, 2018, showing a midlatitude cyclone crossing the Central U.S. with strong frontal thunderstorms in the Midwest and dust lofted behind the front in the Southwest. Image: CIRA/NOAA.

NASA's LANCE, Global Imagery Browse Services (GIBS), and Worldview teams are collaborating with Dr. Miller and operational programmers at NOAA on an effort to add *GeoColor* and similar products to GIBS. GIBS provides quick access to over 900 satellite imagery products that can be viewed using NASA Worldview and similar applications. This NASA/NOAA inter-agency collaboration will further enhance the NRT imagery available for interactive exploration using NASA Worldview.

Using DNB and *GeoColor* imagery, along with LANCE NRT and EOSDIS data, Dr. Miller continues his investigations into the science of the night. And the mysteries of the night persist, including the source of milky sea bioluminescence. Dr. Miller and his colleagues point out that while hypotheses abound, the causes behind

(Continued)

the large swaths of glowing, milky seas remain elusive. Even if their origin can't be pinpointed, though, this ocean phenomenon can't hide from Earth observing satellites that are helping shed light on the shadows of our current understanding.

Representative data products used:

- Terra and Aqua MODIS L1B calibrated radiances; available through LANCE:
  - Terra 1km (MOD021KM; doi:10.5067/MODIS/MOD021KM.NRT.061)
  - Terra 500m (MOD02HKM; doi:10.5067/MODIS/MOD02HKM.NRT.061)
  - Terra 250m (MOD02QKM; doi:10.5067/MODIS/MOD02QKM.NRT.061)
  - Aqua 1km (MYD021KM; doi:10.5067/MODIS/MYD021KM.NRT.061)
  - Aqua 500m (MYD02HKM; doi:10.5067/MODIS/MYD02HKM.NRT.061)
  - Aqua 250m (MYD02QKM; doi:10.5067/MODIS/MYD02QKM.NRT.061)
- Suomi NPP VIIRS imagery; available through GIBS for interactive exploration using NASA Worldview:
  - True Color (Worldview daily global basemap layer)
  - Day/Night Band (DNB), Near-Constant Contrast (NCC)
  - Brightness Temperature, Band M15 (day and night)
- Suomi NPP VIIRS-derived products:
  - Sea surface temperature (VIIRS_NPP-JPL-L2P-v2016.0; doi:10.5067/GHVRS-2PN16); available through NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC)
  - Chlorophyll-a (doi:data/10.5067/NPP/VIIRS/L3B/CHL/2018); available through NASA's Ocean Biology DAAC (OB.DAAC)

Read about the research:

Miller, S.D., Lindsey, D.T., Seaman, C.J. & Solbrig, J.E. (2020) "GeoColor: A Blending Technique for Satellite Imagery." *Journal of Atmospheric and Ocean Technology*, 37(3): 429-448 [doi:10.1175/JTECH-D-19-0134.1].

Miller, S.D., Straka, III, W.C., Yue, J., Smith, S.M., Alexander, M.J., Hoffmann, L., Setvák, M. & Partain, P.T. (2015). "Upper atmospheric gravity wave details revealed in night glow satellite imagery." *Proceedings of the National Academy of Sciences*, 112(49): 6728-6735 [doi:10.1073/pnas.1508084112].

Miller, S.D., Straka, III, W.C., Mills, S.P., Elvidge, C.D., Lee, T.F., Solbrig, J.E., Walther, A., Heidinger, A.K. & Weiss, S.C. (2013) "Illuminating the Capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band." *Remote Sensing*, 5(12): 6717-6766 [doi:10.3390/rs5126717].

Miller, S.D., Haddock, S.H.D., Elvidge, C.D. & Lee, T.F. (2005). "Detection of a bioluminescent milky sea from space." *Proceedings of the National Academy of Sciences*, 102(40): 14181-14184 [doi:10.1073/pnas.0507253102].

Published December 3, 2020

Who Uses Earth Science Data?

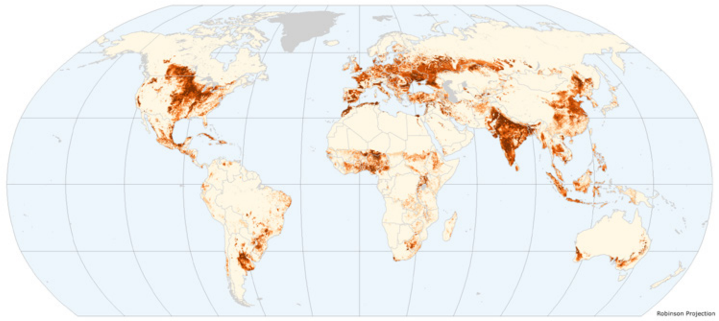
Approximately one-third of Earth's ice-free land surface is devoted to agriculture and livestock. Dr. Ramankutty uses Earth observing data to help find pathways to more sustainable agricultural practices.

Dr. Navin Ramankutty

Professor in the School of Public Policy and Global Affairs and the Institute for Resources, Environment, and Sustainability, University of British Columbia, Vancouver, British Columbia, Canada

Research interests: Dr. Ramankutty uses Earth observing data and models as part of his research into the global patterns and intensity of agricultural land use and the environmental impacts of these actions.

Research highlights: You likely will never encounter a Schomburgk's deer (*Rucervus schomburgki*) in Thailand. Nor will you stumble over a sprig of St. Helena olive (*Nesiota elliptica*) on the island of Saint Helena. These extinct species are among the more than 100 species on the International Union for Conservation of Nature and Natural Resources Red List of Threatened Species whose extinction is attributed to impacts from the conversion of natural areas into agricultural and grazing land. As Dr. Navin Ramankutty and his colleagues point out, the terrestrial biosphere made the critical transition from being mostly wild and natural to being mostly altered by human influence (anthropogenic) early in the 20th century, when the proportion of anthropogenic areas to natural land passed the 50% mark. And this use has consequences.



Global map created by Dr. Ramankutty and his colleagues and available through NASA's Socioeconomic Data and Applications Center (SEDAC) showing the percentage of land devoted to crops in 2000. Darker areas, such as in India and the U.S. Midwest, indicate a higher percentage of land devoted to crops. Data source: Ramankutty, N., Evan, A.T., Monfreda, C. & Foley, J.A. (2010). "Global Agricultural Lands: Croplands, 2000." Palisades, NY: NASA SEDAC (doi: 10.7927/H4C8276G). Accessed 9/2/2020.

In his more than 20 years studying sustainable land and food systems and changes in land use over time, Dr. Ramankutty notes that human clearing of land for agriculture along with the intensification of agricultural production through the use of irrigation, fertilizers, pesticides, and other means has led to significant local and global environmental impacts. Recent data from the World Bank indicate that agriculture, forestry, and land use change are responsible for 25% of global greenhouse gas emissions and 70% of global water use; data from the USDA Economic Research Service (USDA ERS) show that agricultural practices were responsible for 10.5% of 2018 U.S. greenhouse gas emissions.

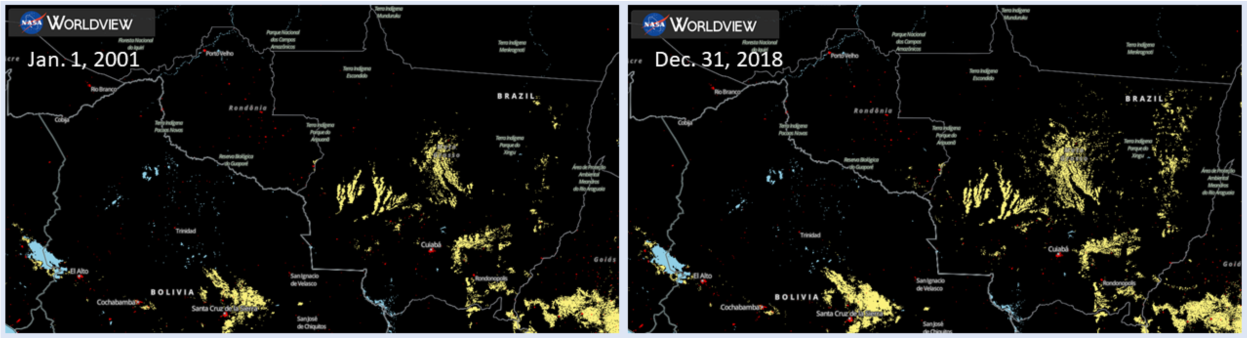
Agriculture, however, also has significant social and economic benefits. It is one of the most powerful tools for ending extreme poverty, according to the World Bank, with growth in the agricultural sector being two to four times more effective for raising incomes than other economic sectors. In the U.S., agricultural production from farms contributed $138.2 billion to the U.S. Gross Domestic Product (GDP) in 2017, according to the USDA ERS, and employment in agriculture, food, and related industries accounted for 22 million jobs (11% of U.S. employment) in 2018.

Balancing the economic and food provision benefits of agriculture with the environmental impacts of current agricultural practices (such as intensive use of fertilizers and irrigation) is where Dr. Ramankutty comes in. His work and research aim to mitigate the environmental

(Continued)

impacts of agriculture, and he observes that this will take a combination of strategies. Some strategies he proposes for creating more sustainable agricultural practices include halting deforestation for non-food crop production, more efficient use of water and nutrients, shifting to more plant-based diets, and reducing food waste.

Data for evaluating these strategies and determining their potential are available through many sources. While agricultural metrics about crop production, water allocation, and energy use are maintained by governmental entities like the USDA and the European Commission, remotely sensed data from Earth observing satellites – data freely available through NASA's Earth Observing System Data and Information System (EOSDIS) – also provide vital information. More than 20 years of daily global imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard NASA's Terra and Aqua satellites, for example, provide the temporal and spatial coverage needed to study land-use change over time, such as the transformation of remote areas into cropland.



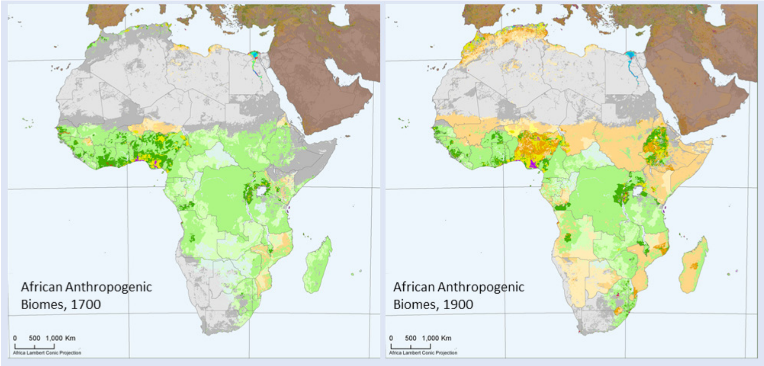
Two Worldview images showing increases in the extent of croplands (yellow areas) and urban areas (red areas) in portions of Bolivia and Brazil between January 1, 2001 (left image) and December 31, 2018 (right image). This is most easily seen in Brazil's Mato Grosso state in the center of the images. Both images are from the MODIS Land Cover Type data product (MCD12Q1), which uses MODIS data from NASA's Terra and Aqua satellites. Click on this URL to do a slider comparison of these images using NASA Worldview: https://go.nasa.gov/2YWPKxL. NASA Worldview images.

Along with using remotely-sensed data in his research, Dr. Ramankutty also uses these data as inputs into datasets that are distributed by NASA's Socioeconomic Data and Applications Center (SEDAC). Hosted at Columbia University's Center for International Earth Science Information Network (CIESIN), SEDAC is the EOSDIS Distributed Active Archive Center (DAAC) responsible for archiving and distributing socioeconomic data in the EOSDIS collection, and serves as an "Information Gateway" between the socioeconomic and Earth science data and information domains.

Dr. Ramankutty and his colleagues pioneered an innovative statistical data fusion technique for merging satellite-derived land cover datasets (such as MODIS land cover data) with ground-based national and subnational cropland inventory statistics (such as census data and agricultural statistics) to develop maps of Earth's cropland and pastures. These were later combined with global population density data to show historical anthropogenic changes to discrete global environmental communities (biomes). Available through SEDAC, the Anthropogenic Biomes data collection comprises five datasets and 35 maps describing globally-significant ecological patterns within the terrestrial biosphere caused by sustained direct human interaction with ecosystems through activities including agriculture, urbanization, forestry, and other land uses.

(Continued)

The Anthropogenic Biomes of the World, Version 1 (2001 to 2006) dataset (doi: 10.7927/H4H12ZXD) delineates discrete anthropogenic biomes based on population density, land use, and vegetation cover, with anthropogenic biomes grouped into six major categories – dense settlements, villages, croplands, rangeland, forested, and wildlands. Anthropogenic Biomes Version 2 comprises four datasets providing information on anthropogenic transformation of the biosphere from 1700 to 2000. As noted by the research team, these datasets have been widely used by the global change community and have been employed in studies including investigations into regional food security, assessments of global regions undergoing rapid land cover change, global carbon cycle modeling and the role of agriculture in carbon cycling, and estimates of global soil erosion.



Map of Africa from the Anthropogenic Biomes Version 2 dataset showing changes in 19 anthropogenic biome categories (colored areas) between 1700 (**left map**) and 1900 (**right map**). Explore the full map gallery at https://sedac.ciesin.columbia.edu/data/collection/anthromes/maps/gallery/search. Maps: CIESIN, Columbia University, September 2013.

In recent research, Dr. Ramankutty explored the potential costs of an intriguing proposal to re-allocate half of Earth's surface back to nature. As advocated by the Half-Earth Project, among other groups, re-allocating half of Earth's surface from uses such as farming or grazing to protected habitat could enable as much as 85% of Earth's known species to survive sustainably, according to figures provided by the Half-Earth Project. While noting that this proposal "is a powerful message that could motivate and empower the public and local organizations to take positive action to protect the biosphere at the level needed to reduce biodiversity decline," the research team also observes that the impacts of this proposal on disadvantaged populations around the world, especially in terms of agricultural and food-production trade-offs, are poorly understood.

An analysis by Dr. Ramankutty and his colleagues incorporating MODIS land cover data with data including calorie production for the world's 41 major crop plants, protected areas, key biodiversity areas, ecoregion boundaries, country boundaries, and potential natural vegetation, shows that implementing a Half-Earth-type proposal could have significant consequences, especially in the developing world. Along with the practical challenges of implementing such a strategy among a multitude of intergovernmental bodies and the fact that agriculture would become even more intense in the remaining 50% of Earth's terrestrial surface, the research team found that a Half-Earth strategy could result in the global loss of 15% to 31% of cropland, 10% to 45% of pastureland, 23% to 25% of non-food calories, and 3% to 29% of food calories from crops. As the team summarizes, "we find no clear pathway to give half our planet to nature at a scale that maintains ecosystem connectivity and still feeds the world, without at least some nations or sub-populations losing out."

Dr. Ramankutty observes that instead of looking for a single best solution, identifying pathways for transformation within specific farming systems may best lead us toward more sustainable agricultural practices. A fusion of satellite-acquired Earth observing data, agricultural statistics, and environmental data is enabling Dr. Ramankutty to identify these pathways and helping him find strategies to ensure the right balance between land use and environmental protection.

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Representative data products co-created or used:

- Datasets available through SEDAC:
  - Global Agricultural Lands Data Collection (Dr. Ramankutty is primary author):
    - Croplands, v1 (2000) (doi: 10.7927/H4C8276G)
    - Pastures, v1 (2000) (doi: 10.7927/H47H1GGR)
  - Global Agricultural Inputs Data Collection (Dr. Ramankutty is co-author):
    - Nitrogen Fertilizer Application, v1 (1994 to 2001) (doi: 10.7927/H4Q81B0R)
    - Nitrogen in Manure Production, v1 (1994 to 2001) (doi: 10.7927/H4KH0K81)
    - Phosphorus Fertilizer Application, v1 (1994 to 2001) (doi: 10.7927/H4FQ9TJR)
    - Phosphorus in Manure Production, v1 (1994 to 2001) (doi: 10.7927/H49Z92TD)
  - Anthropogenic Biomes Data Collection (Dr. Ramankutty is co-author):
    - Anthropogenic Biomes of the World, v1 (doi: 10.7927/H4H12ZXD)
    - Anthropogenic Biomes of the World, v2 (1700) (doi: 10.7927/H4SF2T3M)
    - Anthropogenic Biomes of the World, v2 (1800) (doi: 10.7927/H4NP22C8)
    - Anthropogenic Biomes of the World, v2 (1900) (doi: 10.7927/H4J1012K)
    - Anthropogenic Biomes of the World, v2 (2000) (doi: 10.7927/H4D798B9)
- MODIS/Terra and Aqua Land Cover Type Yearly L3 Global (MCD12Q1; doi: 10.5067/MODIS/MCD12Q1.006); available through NASA's Land Processes DAAC (LP DAAC)

Read about the research:

Mehrabi, Z., Ellis, E.C. & **Ramankutty, N.** (2018). "The challenge of feeding the world while conserving half the planet." *Nature Sustainability*, 1: 409-412 [doi: 10.1038/s41893-018-0119-8].

Ricciardi, V., **Ramankutty, N.,** Mehrabi, Z., Jarvis, L. & Chookolingo, B. (2018). "How much of the world's food do smallholders produce?" *Global Food Security*, 17: 64-72 [doi: 10.1016/j.gfs.2018.05.002].

Ramankutty, N., Evan, A.T., Monfreda, C. & Foley, J.A. (2008). "Farming the Planet: 1. Geographic Distribution of Global Agricultural Lands in the Year 2000." *Global Biogeochemical Cycles,* 22 (1) [doi: 10.1029/2007GB002952].

Published September 24, 2020

Who Uses Earth Science Data?

The ability for Synthetic Aperture Radar (SAR) to create high-resolution imagery regardless of atmospheric conditions makes it a key technology for studies of change over time. Dr. Paul Siqueira's work improves these sensors and the Earth observing data they collect.

Dr. Siqueira at the Bartlett Experimental Forest in New Hampshire conducting forest inventories to compare ground-measured biomass assessments with UAVSAR data. Image by Lake Boddicker.

Dr. Paul Siqueira

Professor of Electrical and Computer Engineering, and **Co-Director** of the Microwave Remote Sensing Laboratory; University of Massachusetts, Amherst, MA

Research interests: Exploring and developing new uses for Synthetic Aperture Radar (SAR) for environmental remote sensing, SAR processing, and ecosystems science.

Research highlights: The one true constant on Earth is change. Some of these changes are relatively rapid, such as new land formed by flowing lava as it cools and solidifies or land deformation caused by the sudden release of pressure holding tectonic plates in place. Some changes, however, are barely noticeable until the change already is occurring, such as a shift in climate over many years leading to changes in the range of plant and animal species along with changes in ecosystem structure and function.

The ability to track environmental change from space using instruments aboard orbiting satellites provides the spatial coverage to study the planet as an integrated system. This is especially important in studies involving entire biomes or ecosystems, which can cover large areas of Earth or discrete areas along a common latitude. Thanks to a continuous record of satellite-acquired Earth observations extending back 40 years or more, much of which is available through NASA's Earth Observing System Data and Information System (EOSDIS), changes to ecosystems over time can be detected, measured, and tracked on a planetary scale. When these data are combined with data acquired from ground-based instruments or airborne sensors, a more complete picture of our planet and its systems is being revealed.

A key technology enabling large-scale environmental research is Synthetic Aperture Radar (SAR). Dr. Paul Siqueira is applying his expertise in microwave sensor instrument development, SAR processing, and ecosystems science to several upcoming and future orbital missions designed to use SAR technology to assess our changing planet with a greater precision than ever before.

SAR is an *active* radar system, and collects data by bouncing a microwave radar signal off a surface to acquire data about that surface's physical properties (*passive* radar systems, such as a radiometer, detect radiated energy and do not send out a radar pulse). Since SAR relies on radar returns to create imagery, it does not need outside illumination. In addition, the wavelengths used for creating SAR imagery can penetrate clouds and smoke to detect properties of tree canopies and soils. This enables SAR imagery to be created day or night, rain or shine across many different ecosystems. NASA's repository for SAR data in the EOSDIS collection, and an important source for the SAR data used by Dr. Siqueira, is NASA's Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC) at the University of Alaska Fairbanks.

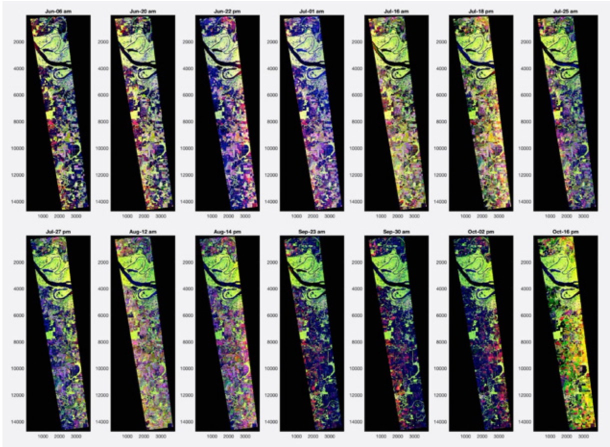
Dr. Siqueira is the Ecosystems Science Team Lead for the upcoming joint NASA/Indian Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) mission, which is scheduled for launch in 2022. NISAR will be the first satellite to systematically map Earth using two different SAR frequencies – an L-band instrument developed by NASA and an S-band instrument developed by ISRO. NISAR will image the entire Earth every 12 days to support research in four primary science areas: ecosystems, hydrology, natural hazards, and the cryosphere. NISAR data will be freely available through ASF DAAC.

NISAR is the latest mission to incorporate L-band SAR, which has a long history of use in Earth observing satellites. The first civilian L-band SAR flew in 1978 aboard the Seasat satellite

(Continued)

(operational June to October 1978), and L-band SAR has been used on numerous international Earth observing missions. Its approximately 24 cm-long wavelength (the second longest of common SAR bands) enables L-band SAR to penetrate the tops of forest canopies to reveal above-ground biomass, making it very useful for ecosystem studies. As noted by the Committee on Earth Observation Satellites (CEOS), a consistent archive of L-band SAR data dating back to the mid-1990s exists for most areas of the world.

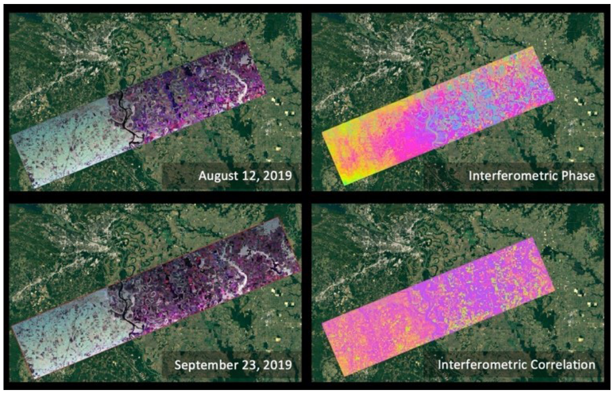
Since NISAR data won't be available until after the satellite becomes operational, Dr. Siqueira and his colleagues are preparing to work with and process NISAR data by using a system called the Uninhabited Aerial Vehicle SAR, or UAVSAR. The UAVSAR pod is mounted underneath a NASA jet and flown in campaigns over specific ecosystems, agricultural areas, and landmasses. Dr. Siqueira was part of the recent NISAR UAVSAR AM-PM campaign, which took place over the Southeastern U.S. in 2019 and used L-band SAR to aid in the development of NISAR ecosystem science algorithms.



A time-series of UAVSAR images collected during the 2019 NISAR UAVSAR AM-PM campaign. These images mimic the observing pattern of NISAR, which will collect one morning (descending) and one evening (ascending) scene for most of Earth's land surfaces every 12 days. Data like these can be used to monitor changes to regional landcover and hydrology, and will be an invaluable record for better understanding the dynamics governing our environment. Image: JPL/Caltech.

Dr. Siqueira also used L-band SAR in his work developing a forest stand height algorithm. A *stand* is a contiguous area containing a number of trees that are relatively homogeneous or have a common set of characteristics. A stand is generally studied or managed as a single unit. Forest stand height (FSH) is defined as the average height of trees in a forest stand, and is a useful metric for characterizing forest stand age, plant and animal habitats, and the amount of above ground biomass in the forest stand. While FSH is generally collected using airborne instruments, the use of satellite-borne SAR enables these measurements to be collected over a much larger spatial area and has important applications in better quantifying and monitoring the global carbon budget.

Dr. Siqueira used interferometric SAR (InSAR) data in his FSH SAR observations. As explained on the NASA NISAR webpage, InSAR techniques combine two or more SAR images acquired over the same region to reveal surface topography, surface elevation change, and the presence of volume scatterers (e.g., leaves, branches, and other objects that can scatter incoming radar waves) in an image called an *interferogram*. When the combined SAR images are acquired from slightly different positions or angles, the topography of the surface can be precisely mapped. The InSAR imagery used by Dr. Siqueira in his algorithm development were from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) mission (operational 2006



An example of an interferogram produced from UAVSAR imagery obtained on two different days in a forested and agriculture region southeast of Little Rock, AR. ***Left images:*** False-color images illustrating a clear distinction between forested and agricultural regions. ***Right images:*** The interferometric products of phase and correlation magnitude provide information on surface change, surface hydrology, and volumetric scattering in the false-color images. Image created by Dr. Siqueira.

(Continued)

to 2011). ALOS PALSAR data are distributed by ASF DAAC through an international agreement with JAXA and are copyright JAXA and the Japanese Ministry of Economy, Trade, and Industry. As Dr. Siqueira observes, an estimate of vegetation height can be determined by the difference between the InSAR-measured height and ground surface elevation acquired from a Digital Elevation Model (DEM).

The launch of NISAR will enable Dr. Siqueira to apply this method of FSH determination over large regions, especially when integrated with lidar data from missions such as the joint NASA/University of Maryland Global Ecosystem Dynamics Investigation (GEDI; launched in December 2018 and installed aboard the International Space Station). Lower-level (Level 1 and 2) GEDI data currently are available through NASA's Land Processes DAAC (LP DAAC); higher-level (Level 3 and 4) GEDI data soon will be available publicly through NASA's Oak Ridge National Laboratory DAAC (ORNL DAAC).

Along with missions scheduled for launch like NISAR, Dr. Siqueira is involved with the planning and formulation for future NASA missions incorporating SAR technology. One objective for future missions is to use satellite-collected InSAR data for studies of surface deformation and change. Deformation measurements acquired using InSAR are an important tool for understanding the dynamics of earthquakes, volcanoes, landslides, glaciers, groundwater, and Earth's deep interior; for quantifying the rates and driving processes of sea-level change and landscape change; and for supporting hazard forecasts and disaster impact assessments. As the Ecosystems Study Lead for NASA's Surface Deformation and Change (SDC) study team, Dr. Siqueira is evaluating the use of SAR and InSAR for future NASA missions. The SDC study started in October 2018 and is scheduled to end in September 2023 with an architecture for a proposed SDC satellite mission.

Of course, change on Earth won't wait for future missions, and continues, sometimes quickly, sometimes inexorably slowly. Through Dr. Siqueira's work, instruments to measure, track, and study these changes and their effect on ecosystems are becoming ever more powerful and are delivering data that are providing a growing understanding of not only the drivers of these changes, but also their potential consequences.

Representative data products used:

- Available through ASF DAAC (additional SAR datasets and products are available using the ASF DAAC Vertex data portal):
  - UAVSAR
    - Polarimetric SAR products (doi: 10.5067/7PEQV8SVR4DM)
    - Repeat Pass Interferometry products (doi: 10.5067/R0ARICRBAKYE)
  - ALOS PALSAR
    - L1.0., L1.1, L1.5
  - Seasat (doi: 10-5067-lz2d3z6bw3gh/)
- GEDI data; available through LP DAAC
  - L1B Geolocated Waveform Data Global Footprint Level (GEDI01_B v001; doi: 10.5067/GEDI/GEDI01_B.001)
  - L2A Elevation and Height Metrics Data Global Footprint Level (GEDI02_A v001; doi: 10.5067/GEDI/GEDI02_A.001)

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- L2B Canopy Cover and Vertical Profile Metrics Data Global Footprint Level (GEDI02_B v001; doi: 10.5067/GEDI/GEDI02_B.001)

- NISAR simulated data from UAVSAR; available through NASA's Jet Propulsion Laboratory UAVSAR Data Search

Read about the research:

Chapman, B., **Siqueira, P.,** Saatchi, S., Simard, M. & Kellndorfer, J. (2019) "Initial results from the 2019 NISAR Ecosystem Cal/Val Exercise in the SE USA." IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 2019: 8641-8644 [doi: 10.1109/IGARSS.2019.8899227].

Siqueira, P. (2019). "Forest Stand Height Estimation." In *SAR Handbook: Comprehensive Methodologies for Forest Monitoring and Biomass Estimation, Chapter 4.* Flores-Anderson, A., Herndon, K., Thapa, R. & Cherrington, E., eds. SERVIR Global Science Coordination Office [doi:10.25966/nr2c-s697]. Available online at https://gis1.servirglobal.net/TrainingMaterials/SAR/SARHB_FullRes.pdf

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Who Uses Earth Science Data?

Water is a finite resource, and the availability of freshwater can have major social impacts. Dr. Eric Sproles uses Earth observing data as part of his studies into water's eco-social effects.

Dr. Eric Sproles

Assistant Professor of Earth Sciences and Director, Geospatial Snow and Water Resources Lab (GEOSWRL), Montana State University, Bozeman, MT

Research interests: Integrating satellite data with land-based and unmanned aerial vehicle (UAV)-collected measurements, geospatial data, and hydrologic models to better understand controls on global water resources and how changing water resources impact social-environmental systems.

Research highlights: When Dr. Eric Sproles looks out his office window at Montana State University, he can watch as winter snow accumulates on the mountains surrounding Bozeman. Snow is good, for a deep snowpack in winter means spring runoff, and spring runoff means freshwater availability for the residents of the Gallatin Valley in which Bozeman sits.

But Bozeman is only a microcosm of not only the importance of water resources, but also of Dr. Sproles' work. Through the use of remotely-sensed data, including data in NASA's Earth Observing System Data and Information System (EOSDIS) collection, his research seeks to better understand the geospatial and climatic controls affecting global water resources and how changing water resources impact social-environmental systems. And as a finite resource, there is only so much water available on Earth.

According to figures available through the USGS, there are approximately 332,500,000 cubic miles of water on, in, and over Earth (to use a more common liquid measurement, one cubic mile is equivalent to approximately 1.1 trillion U.S. gallons, using the Milliliter.org conversion website). While this sounds like a lot, this number is somewhat deceptive. Of this massive amount of water, approximately 97.5% is saline water, mainly in the ocean. Only 2.5% of Earth's water is the freshwater most terrestrial plant and animal life require. Still, this is 8,312,500 cubic miles of water. However, this number also is deceptive.

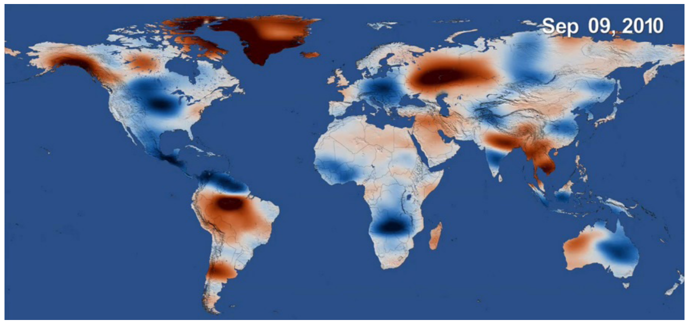
The vast majority of freshwater is locked up in glaciers and icecaps (approximately 5,710,687.5 cubic miles, or 68.7% of freshwater). When you look at readily available groundwater, surface water, or other freshwater (such as water vapor in the atmosphere), this is about 2,601,812.5 cubic miles of water. Complicating matters further, this global freshwater is not only unevenly distributed, but sources of freshwater such as lakes and rivers often cross geopolitical boundaries (this is easily seen in a NASA Worldview image of the Nile River winding through Egypt and Sudan). Incorporating remotely-sensed data (such as satellite imagery) into a Geographic Information System (GIS)-type analysis package not only makes it easier to assess the geopolitical aspects of water, it also helps enable the research by Dr. Sproles into the socio-environmental aspects of water resources.

Dr. Sproles and his colleagues used a combination of geospatial mapping applications, socioeconomic data, and data about changes in Earth's mass acquired by the joint NASA/German Aerospace Center (DLR) Gravity Recovery and Climate Experiment (GRACE) mission to globally assess watersheds extending across geopolitical boundaries and identify regions with a higher probability of experiencing hydro-political tensions from the construction of dams, canals, and other water diversions. GRACE (operational March 2002 to October 2017) used two identical satellites flying in tandem to acquire extremely precise measurements of Earth's gravity field and mass re-distributions. Since water has mass, GRACE data can be turned into products that provide an excellent picture of changes in water resources as shown through changes in Earth's mass at specific locations. The GRACE

(Continued)

data record continues with the joint NASA/German Research Centre for Geosciences (GFZ) GRACE-Follow On (GRACE-FO) mission that launched in May 2018.

The research team looked not only at ongoing development of new dams and water diversions, but also at existing arrangements governing transboundary river basins, such as treaties and formal agreements. The team notes several factors that can exacerbate hydropolitical tensions, including changes in terrestrial water storage (which can be assessed using GRACE data, see image at right), projected changes in water variability, per capita gross national income, domestic and international armed conflicts, and historical instances of disputes over specific transboundary waters. Dr. Sproles and his colleagues note that this study "points to the vulnerability of several basins in Southeast Asia, South Asia, Central America, the northern part of the South American continent, the southern Balkans as well as in different parts of Africa where new water infrastructure is being built or planned, but formal transboundary arrangements are absent." The research team further observes that additional political, environmental, and socio-economic factors in some of these regions could further heighten hydropolitical tensions.



Screenshot from a NASA Scientific Visualization Studio video created using GRACE data collected between 2002 and 2016 showing global changes in terrestrial water storage over time. Blue colors indicate greater freshwater storage than average. Orange, red, and crimson colors indicate lower freshwater storage than average. View this animation at https://svs.gsfc.nasa.gov/12950. Image and animation by NASA's Scientific Visualization Studio.

Closer to home, Dr. Sproles is leading several ongoing projects in his role as director of the Geospatial Analysis of Snow and Water Resources Lab (GEOSWRL) at Montana State University. One EOSDIS resource used by Dr. Sproles and his GEOSWRL team is data from NASA's National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC). NSIDC DAAC archives and distributes EOSDIS data related to snow and ice processes, particularly interactions among snow, ice, atmosphere, and ocean. Located in Boulder, CO, NSIDC DAAC is part of the Cooperative Institute for Research in Environmental Sciences (CIRES), which is a joint institute of the University of Colorado Boulder and NOAA. Dr. Sproles and his GEOSWRL team currently are involved in several snow and ice-related projects.

GEOSWRL
Geospatial Snow & Water Resources Lab

In one USGS-supported project, GEOSWRL researchers are measuring the spatial variability of albedo across the winter landscape. *Albedo* is a measure of the proportion of light reflected by a surface. Fresh, bright white snow has a high albedo and reflects almost all light striking it; older, darker snow and open ground reflect far less light and have a lower albedo. Light that is not reflected is absorbed by an object, which leads to an

Differences in albedo are clearly seen in this image of Dr. Sproles acquiring Global Positioning System (GPS) coordinates in Montana just west of Yellowstone National Park in February 2020 as part of a USGS-funded GEOSWRL project. The high albedo of the snow in which Dr. Sproles is standing contrasts dramatically with the low albedo of the black clothing he is wearing. Note the differences in albedo on the slope of the mountain in the background. Image courtesy of Dr. Sproles

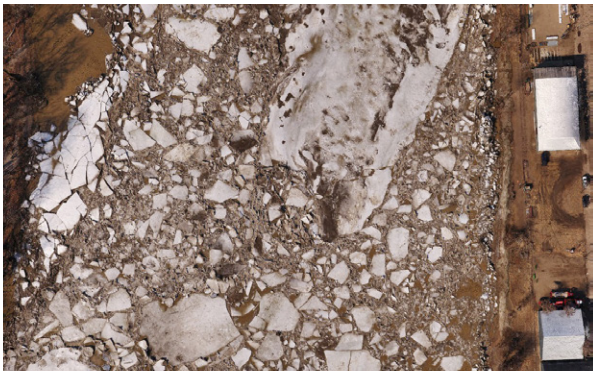
(Continued)

increase in the temperature of the object. Previous research shows that a reduction in albedo, whether through the aging of snow causing it to become darker or through the melting of snow that exposes bare ground, also leads to a localized increase in temperature of these darker areas. This, in turn, contributes to a further reduction in snow cover.

Snow cover data products created from data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Terra and Aqua Earth observing satellites are available through NSIDC DAAC. Along with snow cover and snow extent, these products also include two albedo products (Terra MODIS: MOD10A1, doi: 10.5067/MODIS/MOD10A1.006; Aqua MODIS: MYD10A1, doi: 10.5067/MODIS/MYD10A1.006). Since the ground-based data being collected by the GEOSWRL team are of a higher resolution than the satellite-acquired data from MODIS or from similar instruments aboard the joint NASA/USGS Landsat series of satellites, they will be used to develop methods and technologies to improve the calibration and validation of satellite-borne snow and albedo-sensing instruments.

Another USGS-supported GEOSWRL project is exploring how weather patterns affect snow loading in steep, complex mountain terrain in Montana. This research has direct applications for not only water resource managers, but also for avalanche professionals in the state and beyond. Along with satellite-collected snow cover data, the team is using UAVs to remotely-collect data in mountainous areas that are difficult, if not impossible, to access.

Finally, in Montana's grasslands, the GEOSWRL team is using neural networks to identify and map river ice in the Yellowstone River using NASA and ESA (European Space Agency) data as part of a National Weather Service-supported project. Spring flooding triggered by ice jams on the Yellowstone River damages valuable rangeland in rural communities, destroys bridges and other infrastructure, and severely impacts riparian ecosystems. As Dr. Sproles points out, river ice dynamics on continental rivers like the Yellowstone are not well understood or quantified. He notes that preliminary results from this project and other ongoing GEOSWRL projects shortly will be available through a GEOSWRL website that is under construction.



UAV-acquired image of ice on the Yellowstone River at Glendive, MT, from early-March 2020. The river is approximately 185 meters (about 607 feet) across at this point. The objects on the right side of the image are cars and buildings. Image courtesy of Dr. Sproles.

As winter slowly transitions to spring in the Gallatin Valley, mountain snow is beginning to melt and river ice is starting to break up. Freshwater from these processes will slowly make its way from the mountains and into the valley, sustaining the region for another season. The resulting green-up will be observed not only by residents, but also by instruments aboard Earth observing satellites. The ability to track snow, water, and other hydrologic resources using satellites gives researchers like Dr. Sproles the ability to extend their understanding of this vital resource – and its social and political impacts – far beyond the confines of the Gallatin Valley.

(Continued)

Representative data products used:

- Aqua/MODIS Snow Cover 5-Min L2 Swath 500m, Version 6 (doi: 10.5067/MODIS/MYD10_L2.006); available through NSIDC DAAC
- GRACE monthly land water mass grids NetCDF Release 5.0, Ver. 5 (doi: 10.5067/TELND-NC005); available through NASA's Physical Oceanography DAAC (PO.DAAC)
- GRACE-FO Level-2 Monthly Geopotential Spherical Harmonics GFZ Release 6.0, Ver. 6 (doi: 10.5067/GFL20-MG060); available through PO.DAAC

Read about the research:

Sproles, E.A., Crumley, R.L., Nolin, A.W., Mar, E. & Lopez Moreno, J.I. (2018). "SnowCloudHydro – A New Framework for Forecasting Streamflow in Snowy, Data-Scarce Regions." *Remote Sensing,* 10(8): 1276 [doi: 10.3390/rs10081276].

De Stefano, L., Petersen-Perlman, J., **Sproles, E.A.,** Eynard, J. & Wolf, A. (2017) "Global Assessment of Transboundary River Basins for Potential Hydro-political Tensions." *Global Environmental Change,* 45: 35-46 [doi: 10.1016/j.gloenvcha.2017.04.008].

Sproles, E.A., Roth, T. & Nolin A.W. (2017). "Future Snow? A Spatial-Probabilistic Assessment of the Extraordinarily Low Snowpacks of 2014 and 2015 in the Oregon Cascades." *The Cryosphere,* 11: 331-341 [doi: 10.5194/tc-11-331-2017].

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Code 423
Goddard Space Flight Center
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For more information, please contact
eosdis-outreach@lists.nasa.gov

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