STAR LOOKS AT THE EARTH

SATELLITE MEASUREMENTS OF THE ATMOSPHERE, OCEANS AND LAND

By The Scientists of the Center for Satellite Applications and Research (STAR) and their Collaborators

Edited By:

Alfred M. Powell, Jr
George Ohring
Mike Kalb
Mike Goldberg

National Environmental Satellite, Data, and Information Service
National Oceanic and Atmospheric Administration
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2012

This book is dedicated to our federal and private sector support staff, and to our university partners, whose contributions have facilitated STAR's advances in remote sensing research and applications.

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Section 1

Prelude

In 2012 the Center for Satellite Research and Applications moved to the new NOAA Center for Weather and Climate Prediction building on the campus of the University of Maryland in College Park.

From the Assistant Administrator

The National Environmental Satellite, Data, and Information Service (NESDIS), known as the NOAA Satellite and Information Service, acquires and operates the Nation's operational environmental satellites and maintains long-term archives of global environmental data through its World Data Centers. Our mission is to provide timely access to global environmental data from satellites and other sources to promote, protect, and enhance the Nation's economy, security, environment, and quality of life.

For over 50 years, we have been the world's best at ensuring a continuous uninterrupted flow of environmental data from satellites to weather forecasters and other users. This function is recognized as a Primary Mission Essential Function, or one that is essential to support the continuity of Government. Satellite observations are the foundation on which the Nation's forecasts, warnings, and environmental observational systems are based. Our environmental satellites are key national infrastructure that helps protect lives and property and add immense value to the national economy.

As we continue our current operations, we also plan for the future – our next generation polar-orbiting and geostationary satellite programs, currently in the development stage, are poised to deliver enhanced observations and improve forecasts and warnings. NOAA is investing today to ensure that the Nation can continue to rely on these critical observations for years to come. This key national infrastructure is essential to our Nation's ability to prepare for and deal with severe weather and other environmental phenomena.

The Center for Satellite Applications and Research (STAR) is NESDIS' science office and provides the foundational science information for selecting the measurement bands for monitoring the Earth from satellites, improving our understanding of the Earth and its processes, and transitioning new products and services into operations. This book is dedicated to the efforts of NESDIS' scientific capabilities and the knowledge retained in its people.

NOAA's mission is to understand and predict changes in climate, weather, oceans, and coasts, to share that knowledge and information with others, and to conserve and manage coastal and marine ecosystems and resources. This mission is central to many of today's greatest environmental challenges: climate change, severe weather, natural and human-induced disasters, declining biodiversity, ocean acidification, threatened or degraded ocean and coastal resources. Successfully addressing these pressing issues requires timely and usable information to aid decision-making, and the science that underpins our knowledge of these systems. NESDIS and STAR are key inputs into NOAA's success in addressing these important challenges.

Mary E. Kicza
Assistant Administrator for Satellite and Information Services
National Oceanic and Atmospheric Administration (NOAA)
U.S. Department of Commerce

From the Director

The Center for Satellite Applications and Research (STAR) is the National Oceanic and Atmospheric Administration's (NOAA) premier research office for developing the satellite algorithms needed to transform remote satellite observations to environmental measurements. We strive to improve our monitoring, predicting, and understanding of the environment, while helping to meet the requirements of environmental decision and policy makers. Our team primarily uses the observations of NOAA's operational satellites, but also capitalizes on the measurements of Earth observing research satellites and the satellite data of our international partners. Supported by our university affiliates and contract scientific staff, STAR researches, develops, applies and transitions to routine operations the best methods for monitoring the Earth and its climate.

Science, service and stewardship are the foundational cornerstones of NOAA research. Our select scientific workforce makes STAR research a key contributor to achieving NOAA's goals by providing the highest quality science. The discovery and application of new science and an improved understanding of the planet motivates our staff to develop better products. We are committed to advancing the frontiers of satellite capabilities so that our service can permit cost effective and prudent environmental decisions. Most importantly, our Center takes to heart the need to be good stewards for our country and the planet on which we all live. Understanding how the climate is changing and how it will impact future generations is a fundamental concern. Working to ensure a sustainable environment for our sons and daughters and the generations that will follow them is a primary principle that drives us to be good stewards of our home – Earth.

From the vantage point of space, we can see the changing Earth in its entirety. Since the environmental satellite's inception over 50 years ago, STAR has continued to develop the capability to monitor the ozone hole over Antarctica, track changes in the Earth's vegetation, and measure the recent decline in the North polar ice cap. Satellite observations now provide over 95% of the data used in NOAA's numerical weather prediction models and have been a key factor in improving the reliability of long-range weather forecasts–today's 6-day forecasts are about as accurate as 4-day forecasts were two decades ago. This book highlights our ongoing research and spans the set of atmosphere, ocean and land variables for monitoring the planet and its changes.

This book embodies the heart and soul of the dedicated team of NOAA researchers interested in understanding and improving our stewardship of the planet. It is both dedicated to this group of devoted and passionate scientists and a tribute to their success. May you enjoy the short explanations and images as you learn about the environment. For those who find this work interesting, I hope you will follow our lead and join us in studying the Earth from space!

Alfred M. Powell, Jr
Director, Center for Satellite Applications and Research
Satellite and Information Services
National Oceanic and Atmospheric Administration (NOAA)
U.S. Department of Commerce

Introduction

The first weather satellite was launched into space over 50 years ago. Since that time, advances in space-based Earth observing systems have revolutionized the way we predict the weather, monitor the oceans, assess climate change, and detect environmental hazards. This monograph is a snapshot of the current capabilities of satellites to observe the ever changing global environment, as seen through the research of the scientists of the Center for Satellite Applications and Research (STAR) and their collaborators. The goal is to provide the reader with a book that is interesting, informative, aesthetically pleasing, and easy to digest. It consists of a compilation of 76 short articles, each devoted to a particular research topic and accompanied by relevant illustrations and illuminating sidebars. Every STAR scientist participated in writing this monograph, either as an author or co-author of at least one article. For a number of the articles, they were joined by collaborators from STAR's Cooperative Institutes, and scientists from academia, other government agencies, and the private sector.

The book is divided into five sections. The first contains articles on the basic concepts of satellite observations, the evolution of the international array of Earth observing satellites, the methods used to check on the accuracy of these remote measurements, and the transition of advances from research to operations. The remaining chapters are on the atmosphere, the oceans, the land, and the climate. Each chapter describes applications of satellite observations for monitoring, predicting, and understanding the different aspects of the Earth's environment. Each chapter contains an introductory overview. Most of the articles are on individual environmental variables - e.g., sea surface temperature, atmospheric ozone, etc. Each article places the research topic in context, provides background, explains in simple terms the physical basis for the measurement, captures applications and results, and indicates the contribution of STAR scientists to advancing the research.

NOAA is the primary user of the satellite measurements, but a host of other national and international bodies, both public and private, apply the data and STAR's research results to environmental problems.

We hope you learn something about the "magic" of remote sensing from this monograph, and that you share the excitement of STAR scientists as they expand the application of space-based measurements of the Earth.

Launch of NOAA's latest satellite – the joint NOAA/NASA Suomi National Polar-orbiting Partnership (Suomi NPP) – on October 29, 2011. This next generation polar-orbiting satellite has unprecedented capabilities for observing the Earth's weather, oceans, land and climate. (Photo credit: NASA/Bill Ingalls)

Image of the Earth from the Suomi NPP Visible Infrared Imager Radiometer Suite (VIIRS) observations on January 24, 2012. (Image credit: NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring)

Section 2

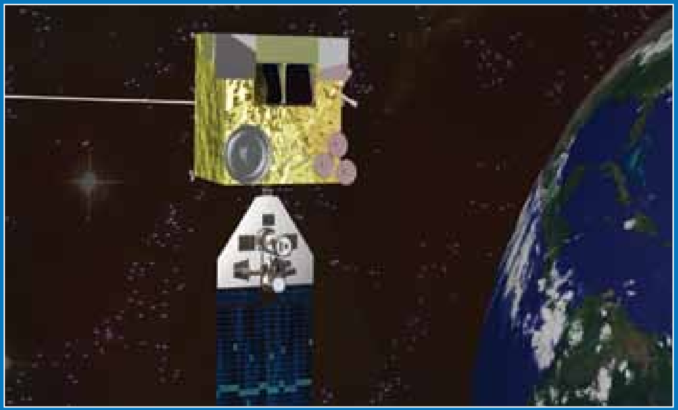
The Satellite System

How many of Earth's artificial satellites are remote sensing satellites?

About 8000 artificial satellites have been launched by countries of the world since the first Sputnik in October 1957. The early satellites were mostly experimental, but they quickly progressed into physics experiments, communications applications, and then remote sensing platforms from satellite orbit.

Although some satellites have multiple purposes, approximately one fifth of the satellite launches can be considered to be Earth, solar, or space science satellites. These satellites help us to understand the Earth and its place in the cosmos and record the Earth's constantly changing atmosphere, land and oceans.

These space observations improve weather and ocean forecast accuracy, enhance environmental monitoring, provide more trustworthy climate observations, and lead to increased knowledge of the Earth system.



A rendering of a GOES Satellite.

Satellite Remote Sensing 101 (Part 1)

Don Hillger

The first two articles present some of the basic concepts needed to understand how satellites measure the Earth's properties from space.

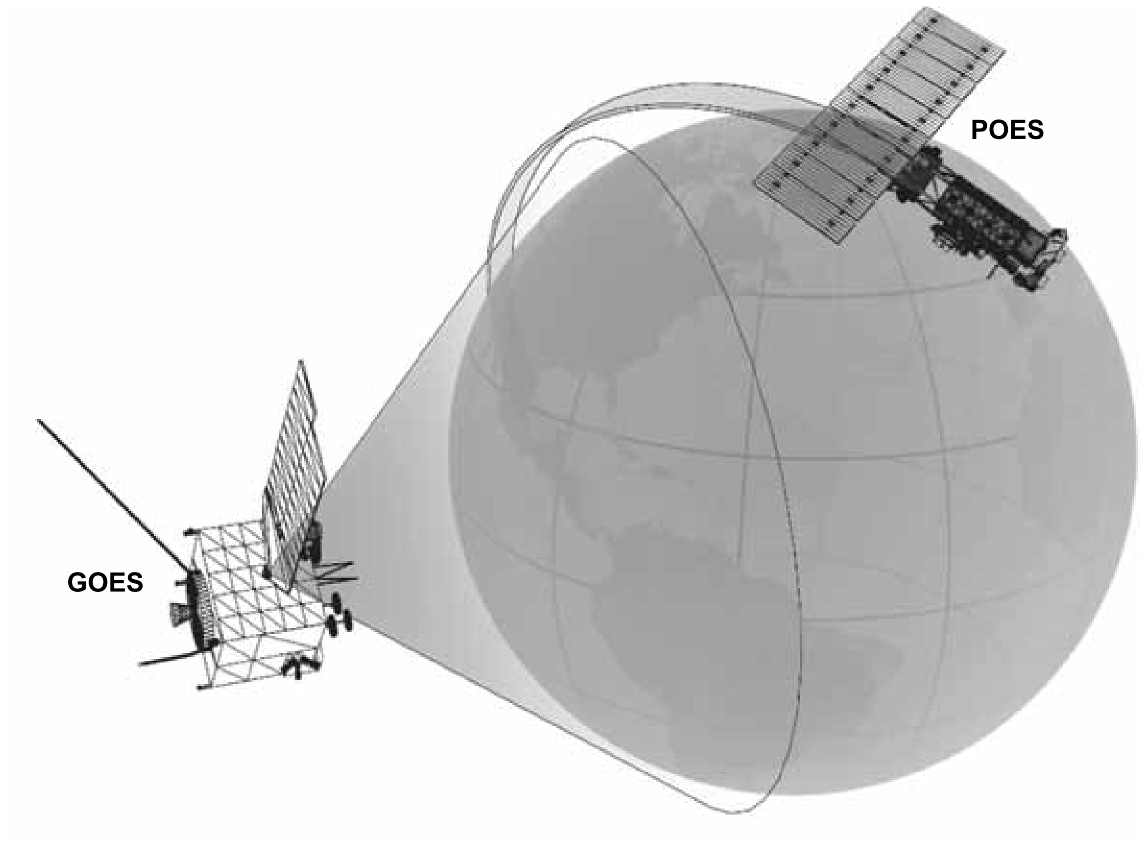
Satellite instruments are either passive or active. Passive instruments – think of a digital camera – measure electromagnetic radiation reflected or emitted by the Earth and its atmosphere. Active instruments – think of radar – send a man-made signal that is bounced off the Earth's surface or its atmosphere before returning to the satellite. In both cases, the measured radiation is sensitive to the surface and/or atmospheric conditions. The signal also depends on light measured from a specific part of the electromagnetic spectrum. For example, clouds are seen in the visible part, temperatures are detected in the infrared.

Satellite instruments have steadily improved, with accurate measurements now available globally at fine spatial resolution, with rapid updates – as frequently as 5 minutes – and at thousands of wavelengths of the spectrum.

NOAA's primary sources of remote sensing data are its own operational satellite systems – the Geostationary Orbiting Environmental Satellites (GOES) series and the Polar Orbiting Environmental Satellites (POES) series (see figure opposite page) – and the operational satellites of other international satellite agencies. Additional observations are available from the research satellites flown by the National Aeronautics and Space Administration (NASA) and other international agencies.

The satellite observations are processed into a wide variety of environmental information products for use in numerous real-time and research applications. These include: weather warnings and prediction; ocean monitoring and prediction; climate monitoring and prediction; tracking snow and ice cover; measuring global sea level; monitoring air pollution; detecting environmental hazards such as fires, volcanic ash, algal blooms, coral bleaching, and microbursts; tracking variations of the Earth's vegetation and drought areas; and checking up on the Earth's ozone layer.

Two Main Types of Weather Satellites



Weather satellites are generally either polar orbiting or geostationary. Polar satellites orbit (circle) the Earth as it rotates beneath them. Each orbit takes about 100 minutes and typically crosses over the poles. Geostationary satellites orbit the Earth near the equator at the same rate the Earth rotates. Thus, they remain stationary with respect to the Earth and constantly monitor the same geographic region. These satellites are the mainstays of NOAA's National Environmental Satellite, Data, and Information Service. While a single geostationary satellite can continuously view a large portion of the Earth, it can only see what is below it. A polar-orbiting satellite can monitor the entire Earth on a daily basis since it sees a different part of the Earth with each orbit. Together, and with more than one of each, these two types of satellites provide the data needed for the analysis and prediction of the Earth's environment.

How are digital satellite images made?

Any image of the Earth consists of pixels (picture elements) of data that are collected successively by either the movement of the sensor or a combination of the movement of the sensor and the satellite. After the data are transmitted down to a ground station, images of the Earth are reconstructed by putting the pixels back into the correct order. Because of finer spatial and temporal resolution, as well increases in the number of spectral bands (channels) that are being measured, the volume of data sent down by satellites has vastly expanded. For example, the next generation of Geostationary Operational Environmental Satellites (GOES) will be sending down about 50 times as much data as current GOES. This huge data stream requires high-speed computers and rapid communications to disseminate real-time remote sensing data for weather analysis and forecasting.

Each day, the next generation GOES satellite will transmit a data stream to Earth, equivalent to all the books in the Library of Congress (above)! (Photo credit: Library of Congress)

Satellite Remote Sensing 101 (Part 2)

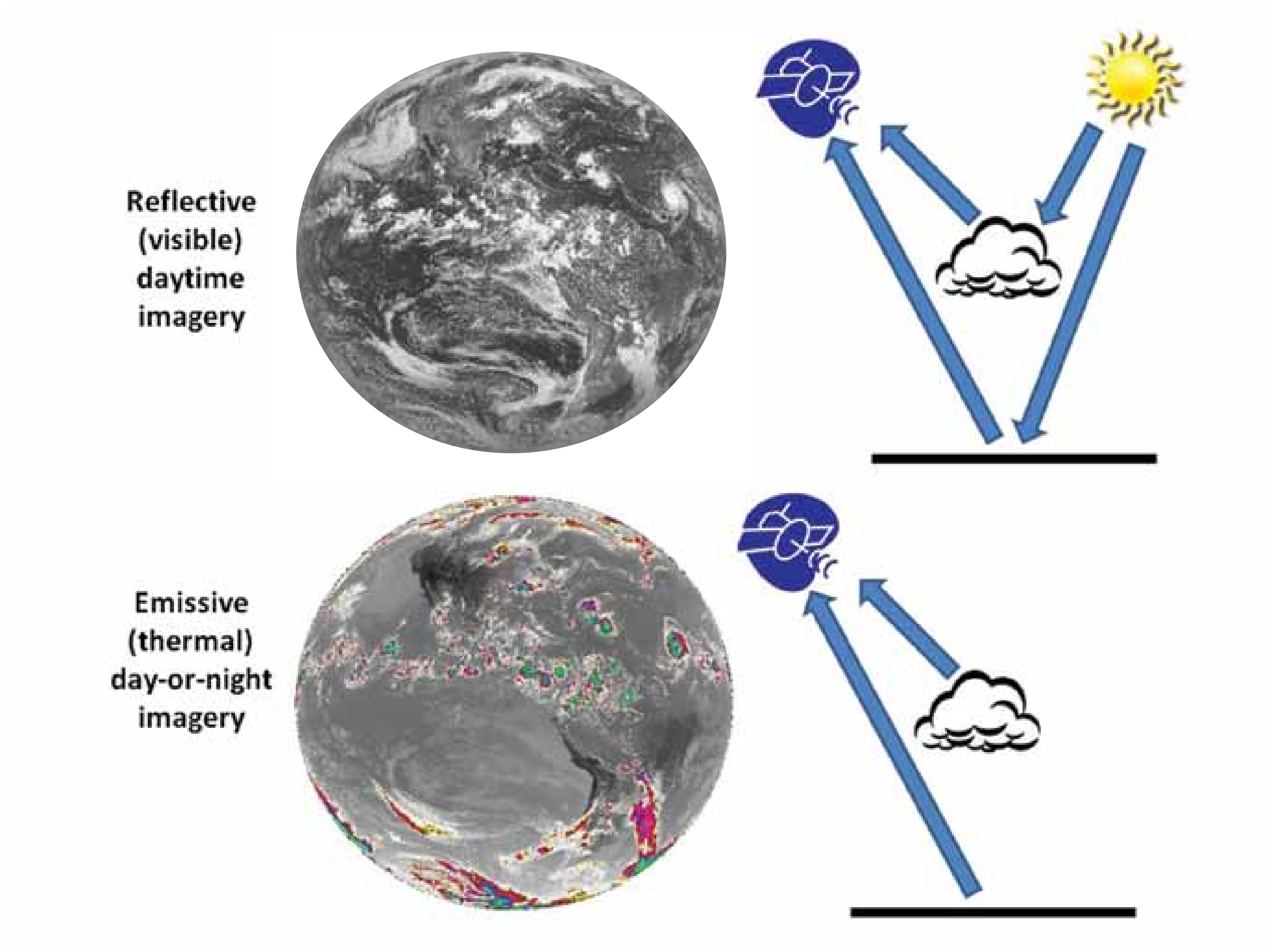
Don Hillger

Remote sensing of the Earth from satellites can be divided into two main types: measurements of solar radiation (sunlight) reflected by the Earth and measurements of thermal radiation emitted by the Earth. Solar radiation is concentrated at short wavelengths – ultraviolet and visible – and thermal radiation at longer wavelengths – infrared (IR) and microwave. The spectrum of reflected solar radiation provides not only images of clouds but also information on snow and ice cover, vegetation, ocean phytoplankton, atmospheric pollutants and ozone. The thermal radiation spectrum is sensitive to surface, cloud, and atmospheric temperatures, water vapor, and other gaseous components of the atmosphere. It's at thermal wavelengths that the Earth can be seen both day and night, making tracking of cloud systems 24 hours a day possible.

While clouds are generally opaque to IR radiation, they are transparent or partially transparent to the longer wavelength microwave radiation, depending on the cloud thickness and microwave observing wavelength. This characteristic of microwave radiation makes it particularly useful for measuring the vertical temperature structure of a cloudy atmosphere as well as the internal structure of clouds and the amount of falling rain.

More recently active satellite instruments – radars and lidars (radio and light detection and ranging) – have come into use. Their main advantage is the ability to determine, with very high accuracy, the heights from which the radiation that they pulse toward the Earth is being reflected, allowing, for example, measurements of sea surface height with an accuracy of centimeters. Another type of active measurement is based on the radio signals emitted by the high altitude GPS satellites – the same system used by our GPS devices. By measuring, from low Earth-orbiting satellites, the GPS radio signals that have traversed the atmosphere, very accurate information on atmospheric temperature can be derived.

Remote Sensing at the Visible and Infrared Wavelengths



Although remote sensing is most common at visible/reflective and infrared/emissive wavelengths, much of the electromagnetic spectrum can be measured. These measurements reveal characteristics of the land and ocean surfaces, the many types of clouds in the atmosphere, as well as the atmosphere itself. Satellite images can be enhanced by the addition of color (for example, the thermal radiation image above, with high, thick clouds in color), or images can be combined to create various products and services that are useful for detecting or discriminating features of interest.

Then and now!

The Television and Infrared Observation Satellite (TIROS 1) was launched on April Fool's Day (1 April) 1960. The figure below shows the first photograph ever taken by a weather satellite. On-board was a modified television camera (Vidicon). The satellite lasted 78 days and produced 23,000 pictures. It revealed a tropical cyclone off the coast of Australia.

Image of Hurricane Katrina from the current GOES satellite. Since the mid-1960s no tropical cyclone has gone undetected. (Photo credit: NASA (top))

Evolution of the Global Satellite Observing System

Laurie Rokke and Mitch Goldberg

The following banner headline ran across all six columns of the first page of the New York Times on April 2, 1960.

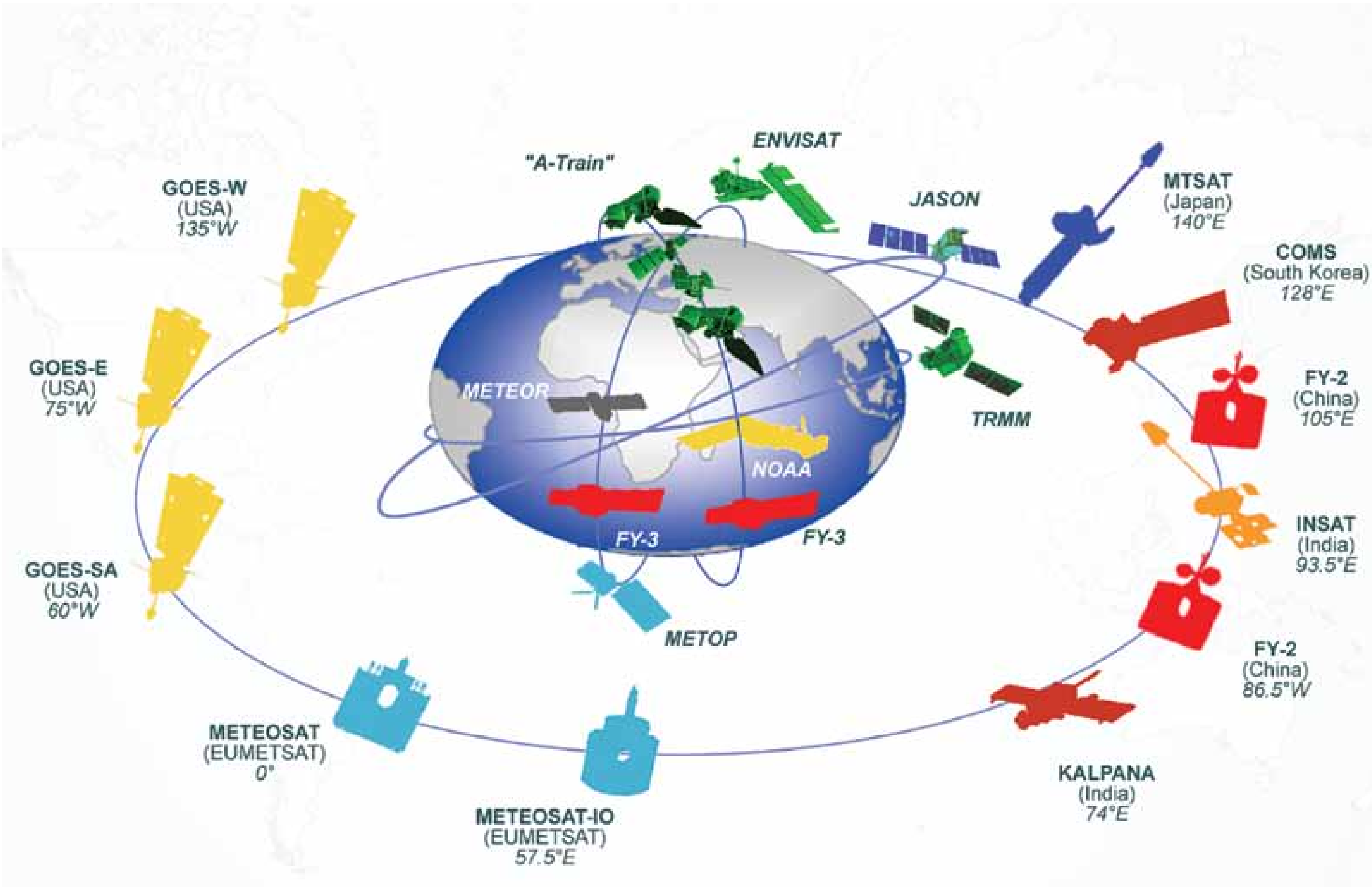
U.S. ORBITS WEATHER SATELLITE;
IT TELEVISES Earth AND CLOUDS

The satellite produced pictures of clouds and storms around the globe that might have otherwise gone undetected for days using conventional observation methods. The first geostationary satellite – the Applications Technology Satellite - launched in 1966-67, took the first color images of the Earth. Advances in instrumentation expanded the observational spectrum from the visible and infrared to the microwave region, which enabled measurements through clouds, and to the ultraviolet for ozone measurements. Finer spectral and spatial resolution and more frequent measurements from the increasing number of polar and geostationary satellites in the space-based global observing system (see figure opposite page) now provide continuous three-dimensional monitoring of the Earth's surface and atmosphere.

STAR scientists are active participants in the Coordination Group for Meteorological Satellites (CGMS) and the Committee on Earth Observation Satellites (CEOS), international bodies that coordinate the development of space-based observations. STAR was a founding member of the Global Space-based Inter-Calibration System (GSICS), an international collaboration to monitor, improve and harmonize data quality from operational environmental satellites.

STAR is contributing to the development of the next generation of NOAA geostationary – GOES-R – and polar – the Joint Polar Satellite System (JPSS) – satellites, which will have advanced capabilities to meet the nation's ever expanding needs for accurate and timely environmental data.

The Global Satellite Observing System

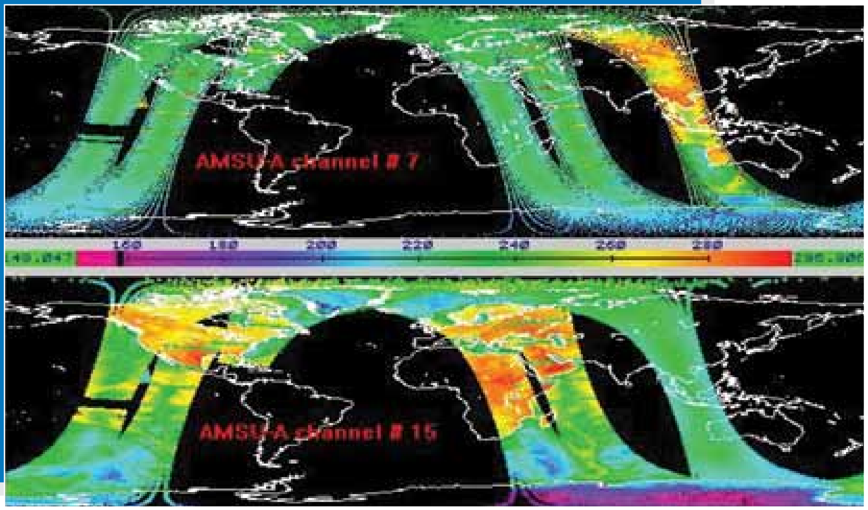


Schematic diagram of the global satellite observing system. Low Earth orbiting satellites (LEOs, inner rings) circle the Earth at about 800 km in about 100 minutes. Polar orbiting LEOs can provide daily global coverage as the Earth spins beneath them. Geostationary satellites (GEOs, outer ring) orbit the Earth at the same rate as the Earth rotates. As a result, geostationary GEOs observe the same locations day and night. Recently launched LEO satellites not appearing in this diagram include the U.S. Suomi National Polar Partnership (NPP) in late 20011 and the Japanese Global Change Observation Mission 1 (GCOM-1) in 2012. (Photo credit: WMO)

Mass producing a catapult!

The transition of new ideas into successful products has been a problem since at least the time the Romans failed to transition their recently designed catapult into mass production. Despite the best efforts of satellite research to operations transition teams, unforeseen instrument problems may occur. The transition teams are constantly on high alert to detect and correct malfunctions.

The figure below shows data from the NOAA-15 Advanced Microwave Sounding Unit (AMSU-A). The R2O team immediately detected and resolved a serious problem seen in the rightmost orbital swath. Channel 7 (upper panel), which observes at a microwave frequency sensitive to the atmosphere, had been swapped onboard the instrument with the surface observing channel 15 (lower panel) – the channels had been incorrectly wired. The simulated solution to this problem - shown on the next two orbits – led to the corrective action by STAR scientists, instrument engineers, and operational personnel that overcame this major flaw for the remainder of its multi-year mission.



Research to Operations

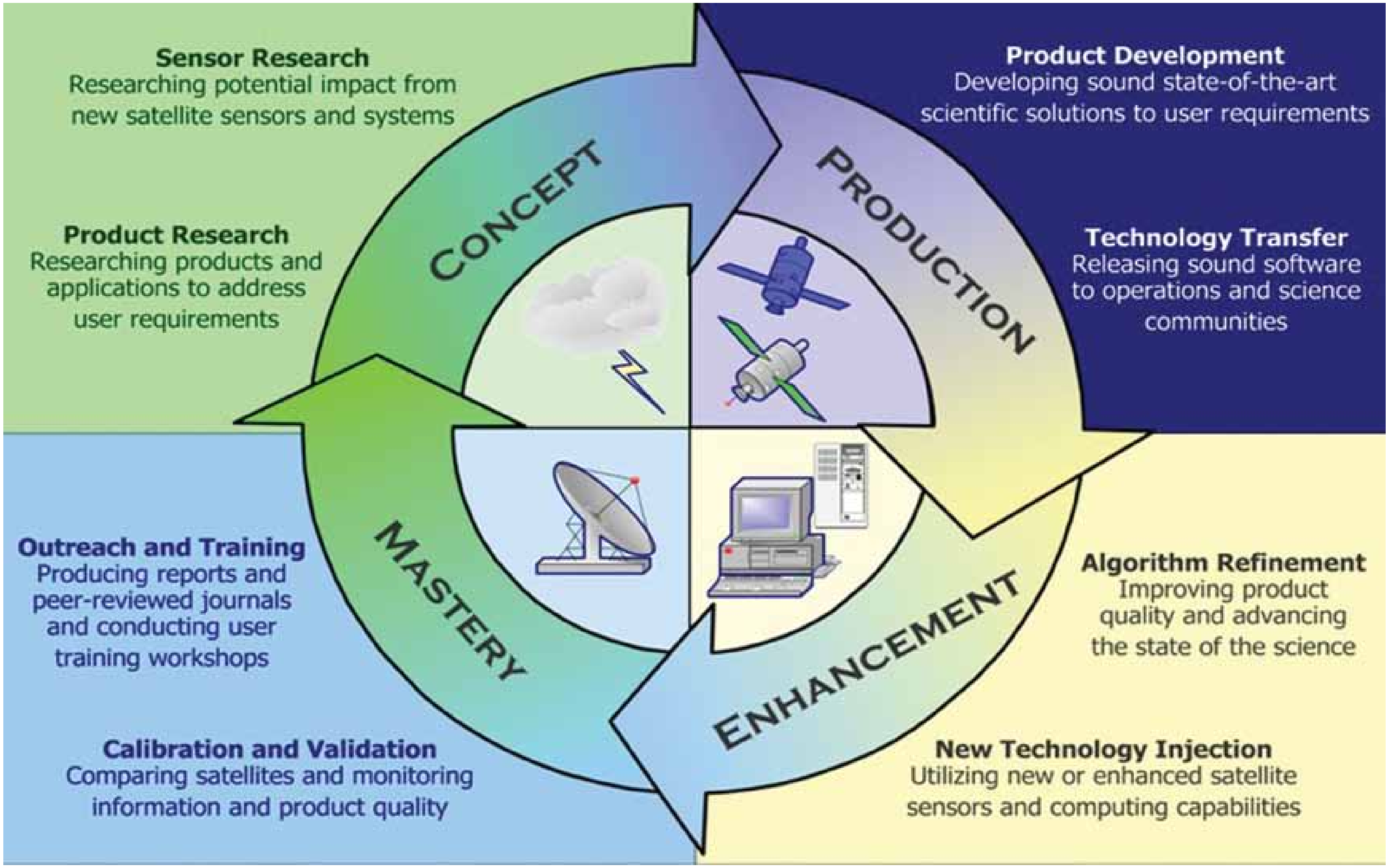
Michael Chalfant and Laurie Rokke

STAR provides the science that turns satellite data into products that support NOAA operational missions 24 hours a day, 7 days a week. Challenges to the successful transition from research to operations (R2O) include satisfying many different customers, extracting the maximum information from instruments that sense remotely, and developing data processing systems that transform raw satellite observations into geophysical products in near-real time (minutes to hours). A lifecycle of satellite products from requirements to retirement/replacement is shown in the chart on the opposite page.

New satellite data product requests come in from NOAA's weather, ocean, and climate operations. With the assistance of STAR scientists, instruments are designed to meet these needs and launched into space. Once the instrument specifications are finalized, STAR scientists set to work to create the needed products. They develop algorithms - a series of mathematical steps - for processing the observations. Teams of programmers, computer scientists and engineers develop and transition the often complicated science code into streamlined and standardized programming languages that can meet the demands of the operational environment. The teams also track and document changes to the algorithms, take into account instrument anomalies, and monitor and update the science and operational code as the instruments age. A NESDIS board reviews and approves all new operational products, enhancements, and updates to existing products.

The next generation of satellites to be launched into polar and geostationary orbits will fulfill a host of additional NOAA requirements and provide new challenges for the R2O transition teams to develop, validate and maintain these products in operations.

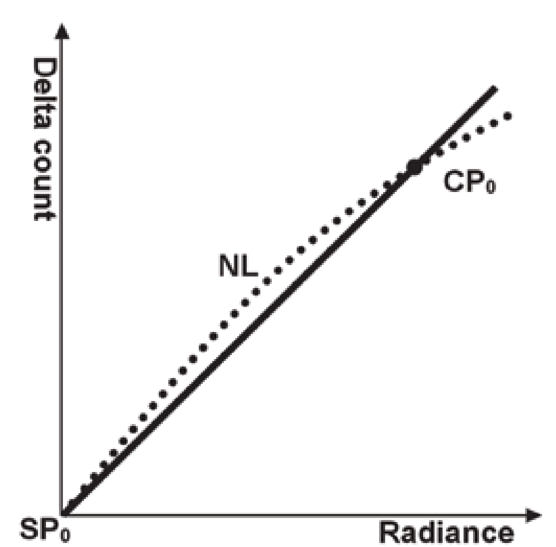
From Concept to Mastery



The life cycle of a satellite product.

Ice, boiling water, and calibration

Most satellite instruments use two relatively well-known points for calibration – similar to using the freezing and boiling point temperatures of water for calibrating thermometers. One is typically the space-view, or SP_0 in the figure below (left), and the other is an onboard source of known amount of radiation, or calibration point CP_0. This device is typically a blackbody for the infrared and microwave instruments, and a solar diffuser (reflector) or lamp for the solar or visible bands. Assuming that the instrument has a linear response to incoming radiation, a perfect two-point calibration system would be sufficient to calibrate all satellite observations (delta counts in the figure) to radiances. If pre-launch laboratory measurements indicate that the calibration is non-linear, a curve such as NL would be used.



Calibration

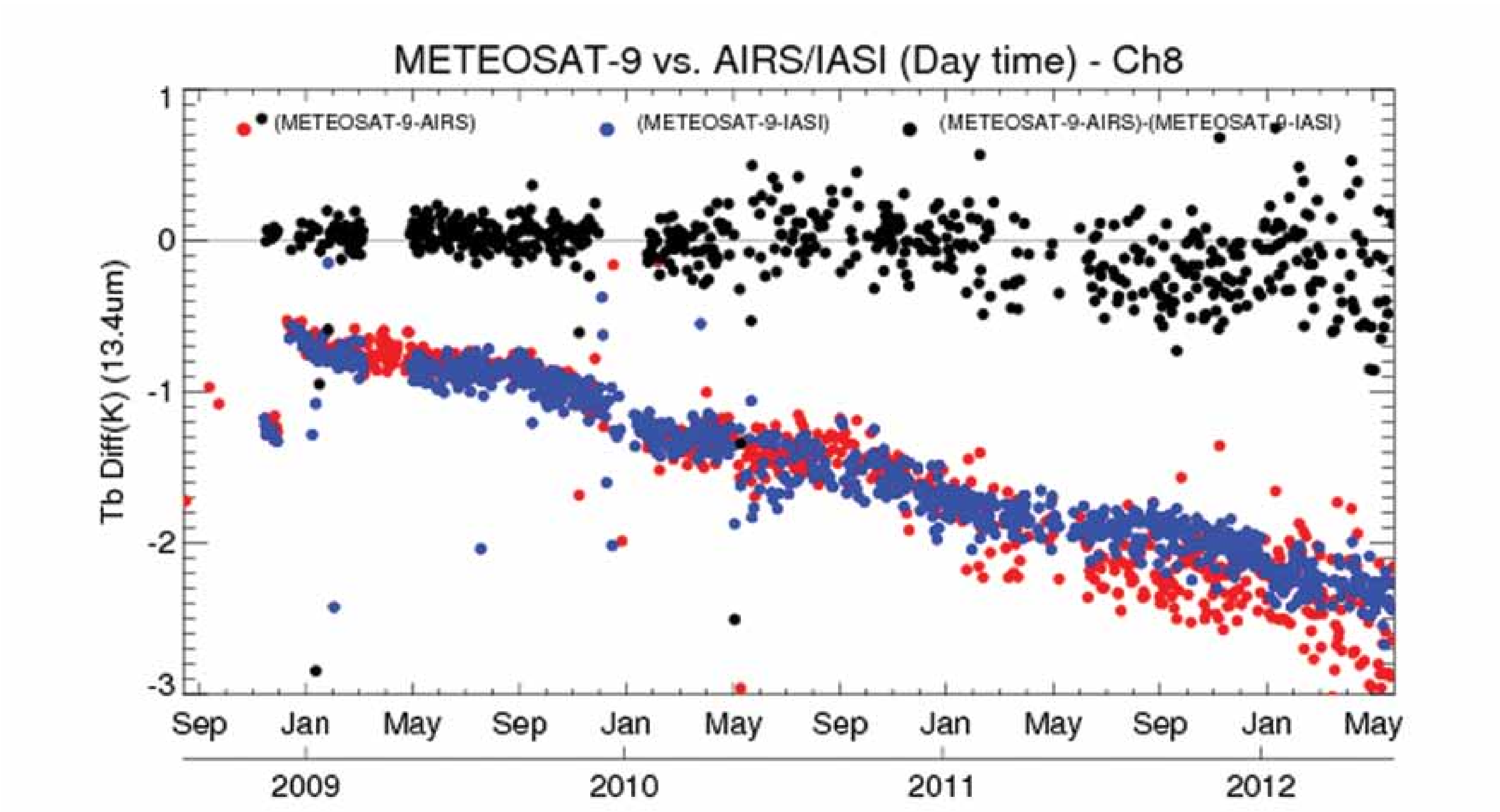
Changyong Cao, Xiangqian Wu, Robert Iacovazzi, and Fangfang Yu

Measuring the Earth's reflected and/or emitted radiation from satellites is similar to taking photographs with a digital camera. A major difference, however, is that the digital data in Earth observations have to be calibrated and converted from unitless digital numbers to a measure of radiant energy – radiances – with a physical unit (see sidebar). The calibration must be traceable to reference standards so that the instrument's observations can be compared with other measurements. STAR scientists are responsible for ensuring that NOAA's satellite instruments provide reliable data.

Climate change detection provides an especially demanding challenge for calibration accuracy and consistency since the signal can be very small, e.g., about 0.1 to 0.2 degrees Centigrade (C) per decade for temperature changes. Also, since satellite instruments last only about five years, observations from instruments on a series of satellites are used to establish climate trends. But even the same series of radiometers do not automatically produce consistent measurements. Our team then steps in and maintains consistency.

To attack this problem, the World Meteorological Organization (WMO) organized the Global Space-based Inter-Calibration System (GSICS) to ensure the comparability of measurements from all satellites. Since its inception in 2006, 15 national and international agencies, including all weather satellite operators and other space agencies around the world, have joined the program. GSICS helps to provide consistent measurements from all satellites, from all countries, to support the environmental monitoring and prediction missions of NOAA and other agencies. STAR played a key role in organizing GSICS, co- chairs its Executive Team, and houses the GSICS Coordination Center to ensure that the many satellite instruments are accurately calibrated.

Correcting for Instrument Drift



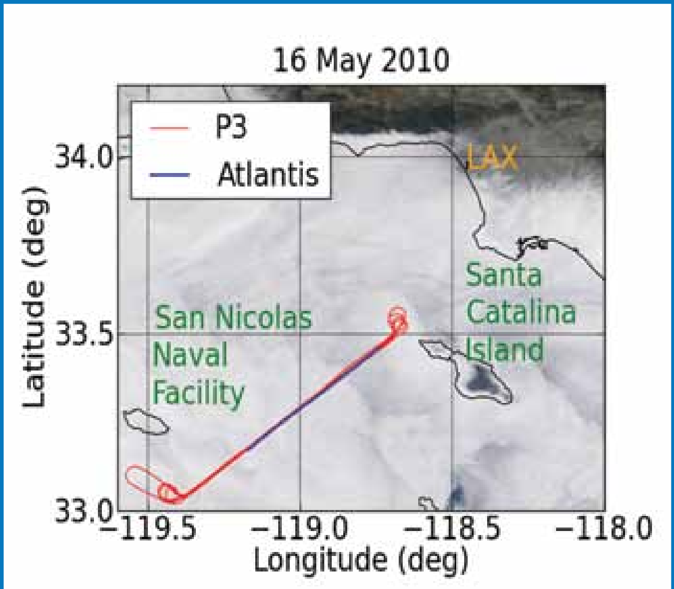
In support of the Global Space-based Inter-Calibration System, STAR scientists have designed, implemented, and routinely operated a system to inter-calibrate the infrared channels of all the geostationary weather satellites with the well calibrated hyperspectral (thousands of observing channels) instruments: NASA's Atmospheric Infrared Sounder (AIRS) and Europe's Infrared Atmospheric Sounding Interferometer (IASI). In this example, a European geostationary satellite, METEOSAT-9, is compared with AIRS (blue) and IASI (red) for one of its many channels over a period of two and a half years. The degradation of the Meteosat IR channel with respect to AIRS and IASI is clearly shown by the sloping red and blue lines of dots. These data also demonstrate the high consistency of AIRS and IASI observations (black dots).

Validation of GOES cloud retrievals

STAR scientists collaborated with researchers from the University of Colorado and the NOAA Earth System Research Laboratory to use data collected during the NOAA CalNex field mission to validate experimental GOES cloud retrievals.

On May 16th, 2010, the Woods Hole Oceanographic Institution research vessel "Atlantis" and the NOAA P3 aircraft conducted joint measurements within a marine cloud layer west of Santa Catalina Island off the coast of Southern California.

The GOES cloud retrievals are compared to the ship and aircraft measurements. Satellite observations are considered validated when they agree with the other measurements.



Checking the Measurements

R. Bradley Pierce, Andrew Heidinger, Sebastian Schmidt, and Sara Lance

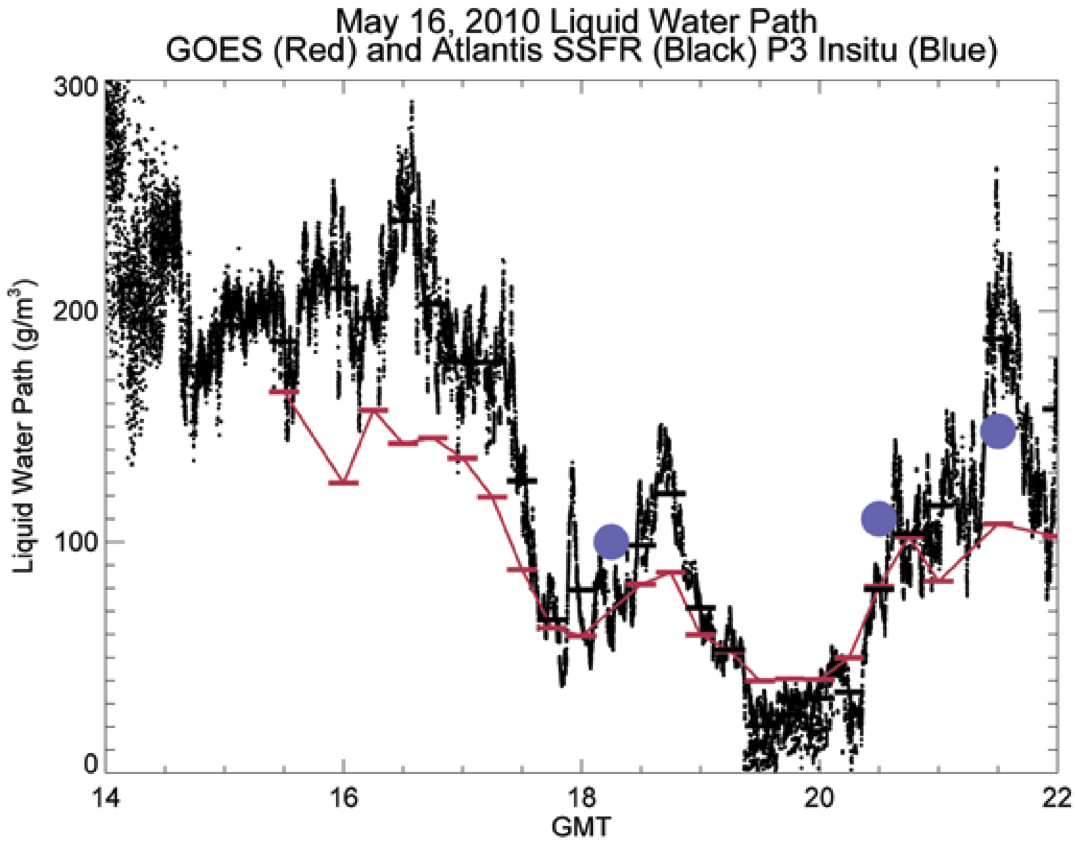
When an instrument is placed directly in or on an object to measure its properties – for example, thermometers measuring air temperature – the measurement is called a direct measurement. Satellite observations of geophysical variables are indirect measurements: they depend on a conversion – through the atmospheric radiative transfer equation – of the remotely sensed radiance to the variable of interest, a process referred to as "retrieval". The quality of the retrieval is not only dependent on the accuracy of the radiance measurements – see discussion in article on calibration – but also on uncertainties in the radiative transfer equation. In many cases, other factors besides the variable of interest affect the observed radiation signal, and these must be properly accounted for in the retrieval procedure.

Validation is the process of checking the quality of the satellite retrievals using independent and more accurate measurements, that is, by comparing them with observations from another source. Independent measurements include in-situ networks – weather stations, radiosondes, ozone and aerosol networks, ocean buoys and ships – and special aircraft and research campaign measurements.

The sidebar and the figure on the opposite page illustrate the use of field campaign measurements to verify satellite-based measurements of cloud properties. The field measurements – in this case aircraft and ship observations – are carefully coordinated with the satellite passes.

Understanding the quality of the satellite retrievals is crucial to monitoring, predicting, and understanding the Earth/atmosphere system. Validation provides the traceable estimates of the reliability of satellite retrievals that are necessary to make informed use of the data. Validation of satellite retrievals is a major part of STAR's program.

Validating GOES Cloud Retrievals with Aircraft and Ship Observations



Time series of the GOES (red) and Atlantis (Ship) Solar Spectral Flux Radiometer (SSFR) (black) retrievals, and P3 (Aircraft) in-situ (blue) measurements of Cloud Liquid Water during the NOAA P3 rendezvous with the Woods Hole Research Vessel Atlantis on May 16, 2010. Airborne in-situ measurements from cloud probes onboard the NOAA P3 research aircraft provide direct measurements of the microphysical properties of the clouds, which can be used to understand differences between the GOES and SSFR retrievals.

The NOAA Products Validation System

Anthony Reale and Bomin Sun

The previous article describes how specially conducted field observations are used to check satellite retrievals. Here we show how STAR leverages existing observational networks to verify the satellite measurements.

STAR has developed the NOAA Products Validation System (NPROVS). NPROVS relies on global "ground truth" observations, typically from weather balloons (radiosondes and dropsondes) and numerical weather prediction (NWP) models to estimate the prevailing atmospheric conditions at a given location and time. These are then compared to atmospheric measurements from polar (NOAA, MetOp, DMSP and NASA), geostationary (GOES) and occulting satellite platforms at the same times and locations. An example of an occulting satellite is the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) where signals traverse the limb of the Earth from one satellite to another, versus being reflected from the Earth's surface. A comparative analysis of these measurements yields information on the quality and integrity of the satellite data.

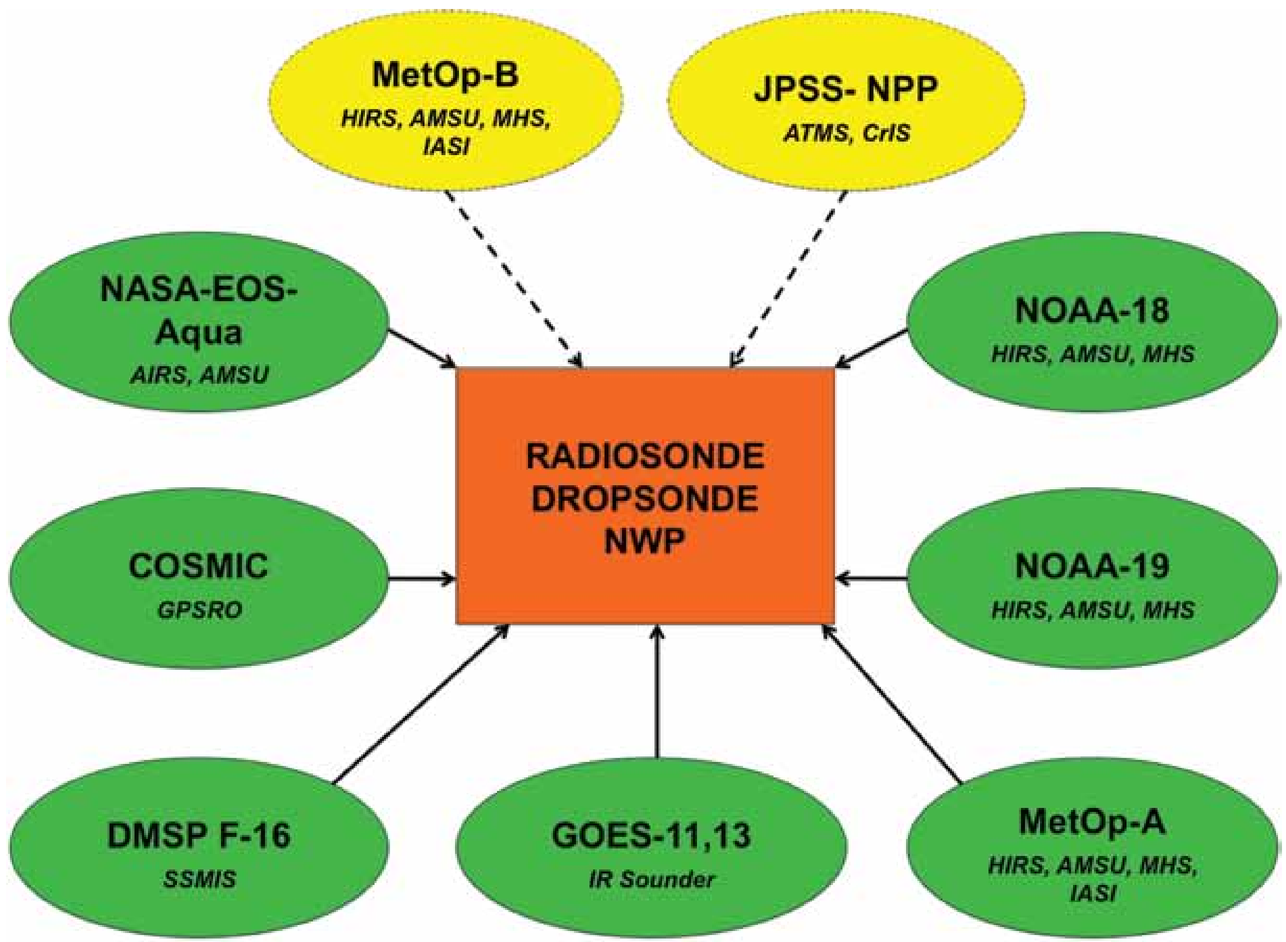
NPROVS is the first system to combine satellite observations from polar, geostationary and occulting sensor technologies into a single dataset collocated to common ground truth measurements. NPROVS will play a key role in the validation and deployment of advanced next generation satellite sensors and products. Goals include the compilation of long-term records linking the performance of past, present and future environmental observations and the construction of homogeneous observations to monitor climate.

A stamp of approval

NOAA spends billions of dollars annually on programs to design, build and operate multiple Earth orbiting satellites and a variety of onboard environmental sensors. The primary objective is to provide critical information in support of NOAA's mission goals in weather, ocean, climate and other environmental applications. However, it is not enough to simply collect data – how do we know that the measurements are correct? Validation – the process of checking the satellite measurements against reliable, independent observations – allows NOAA to provide a "stamp of approval" on the space-based measurements.

Collocated satellite and weather balloon observations (radiosondes) processed by NOAA's Products Validation System are a key contribution to validation of multiple satellite sensors and derived weather products on a global scale. (Photo credit: NOAA/NWS/Robin Ingram, Sara Presnall, and Art Wildman)

Routine Global Monitoring of Satellite Weather Products



NOAA's Products Validation System (NPROVS) routinely compares global atmospheric weather data derived from sixteen environmental sensors (in italics) onboard eight different satellites (green) against collocated radiosonde, dropsonde and numerical weather prediction (NWP) forecast and analysis data (red). Next generation satellites to be added to the system include NOAA's Joint Polar Satellite System (JPSS), the NASA-NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) satellite (launched in 2011 as the precursor to JPSS), and MetOp-B (yellow). NPROVS collocation datasets are compiled daily and long term records are archived at STAR.

Why near real-time online monitoring?

STAR develops improved products. Their performance should be evaluated against heritage products, and their improvements should be demonstrated.

Similar products are generated by STAR partners. STAR wants to know how its products are performing relative to these counterparts.

Near-real time monitoring is needed to objectively evaluate the quality of STAR products and quickly fix anomalies in operational data.

Online monitoring is needed to effectively communicate status and quality of STAR products to data users, developers, and managers.

Quality monitoring is also the key element in the development and verification of Climate Data Records (CDR).

STAR scientist Alex Ignatov checks the quality of satellite sea surface temperature measurements using the web-based monitoring system.

Web-Based Monitoring

Alexander Ignatov, Xingming Liang, Prasanjit Dash, Feng Xu, and John Sapper

With the expanding operational applications of satellite products and the ever increasing number of users, an easily accessible, comprehensive, and consistent monitoring and verification system is needed to:

- Provide fully automated, online, timely, and global monitoring
- Monitor in-situ data used for checking the satellite product
- Monitor satellite radiances associated with the satellite product

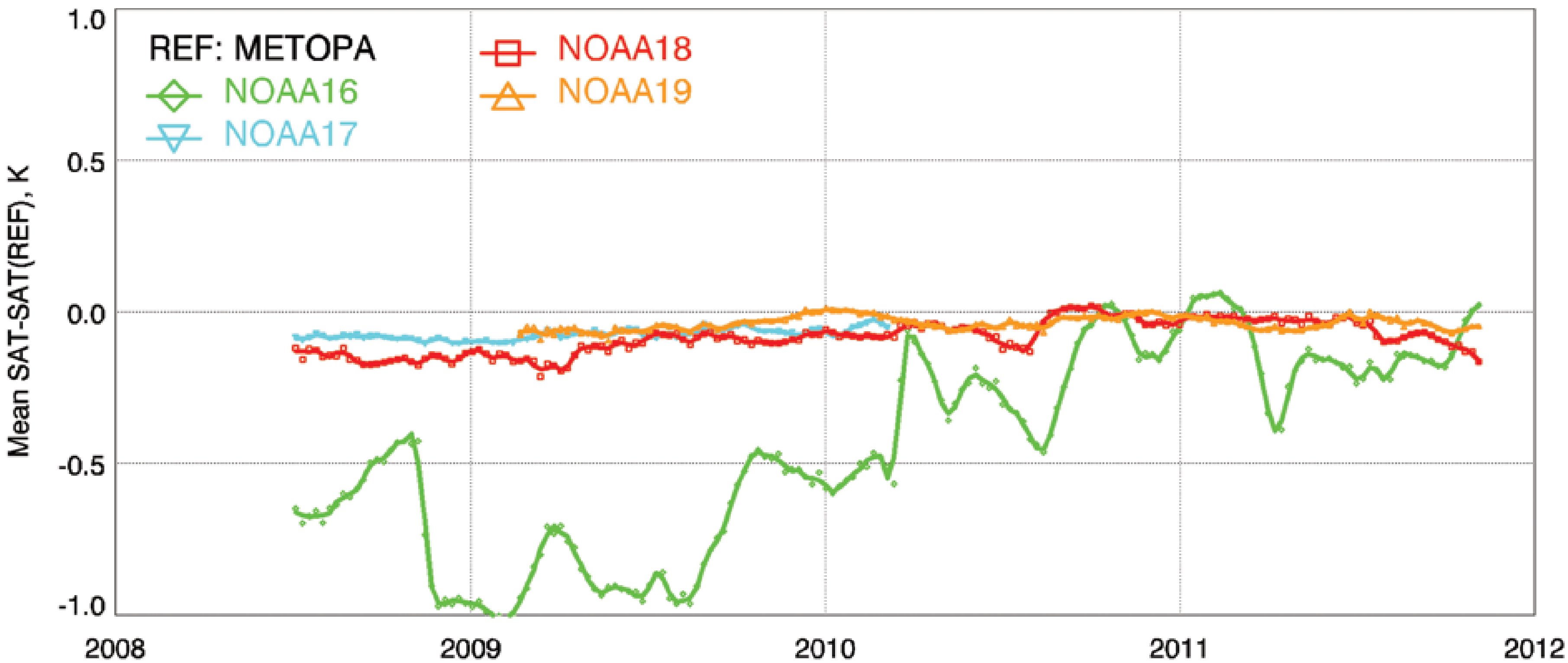
A key feature of a prototype system recently developed by STAR for monitoring sea surface temperatures (SST) is its timeliness – it is done in near real-time, that is, immediately after the satellite observations have been made.

The web-based system consists of three components:

- The Satellite SST Quality Monitor tracks various SST products for stability, analyzes them for self- and cross-consistency, and verifies them against quality controlled in-situ data.
- The in-situ SST Quality Monitor performs quality control of in-situ SST data, monitors them on-line, and serves them to outside users.
- The system for Monitoring of IR Clear-sky Radiances over Oceans for SST keeps tabs on the clear-sky radiances (brightness temperatures) of the ocean – from which the SSTs are derived – using a radiative transfer model in conjunction with atmospheric information from an NWP model to simulate the satellite clear-sky radiances.

This near real–time, web-based system makes the SST verification data easily and quickly accessible to STAR scientists and the user community.

Web-based Monitoring of Sea Surface Temperature



Systematic differences – biases in nighttime SST between the four NOAA Advanced Very High Resolution Radiometer (AVHRR) instruments on NOAA-16, -17, -18, -19 and a reference satellite, Metop-A – as seen in STAR's prototype online system. Generally, the systematic differences are small – less than 0.2 °C – and stable, except for the NOAA-16 AVHRR (green curve), whose suboptimal calibration affects the quality of the derived SSTs – biases are not stable and are as large as -1 °C. Work is underway to improve the calibration of the NOAA-16 AVHRR, and test the effect on SST consistency using the on-line system.

Section 3

The Atmosphere

Ice crystal habits

Water is one of the few atmospheric constituents that can exist in all three phases (solid, liquid, gas) under the normal range of atmospheric temperatures. The ice phase is extremely complex, where a multitude of crystal habits (shapes) exist. Small variations in temperature and moisture content lead to very different structures, although most have a hexagon appearance. Below are several examples of atmospheric ice crystals many of which are very aesthetically pleasing.

(Photo credit: www.Snowcrystals.com)

The Atmosphere

Mark DeMaria and Debra Molenar

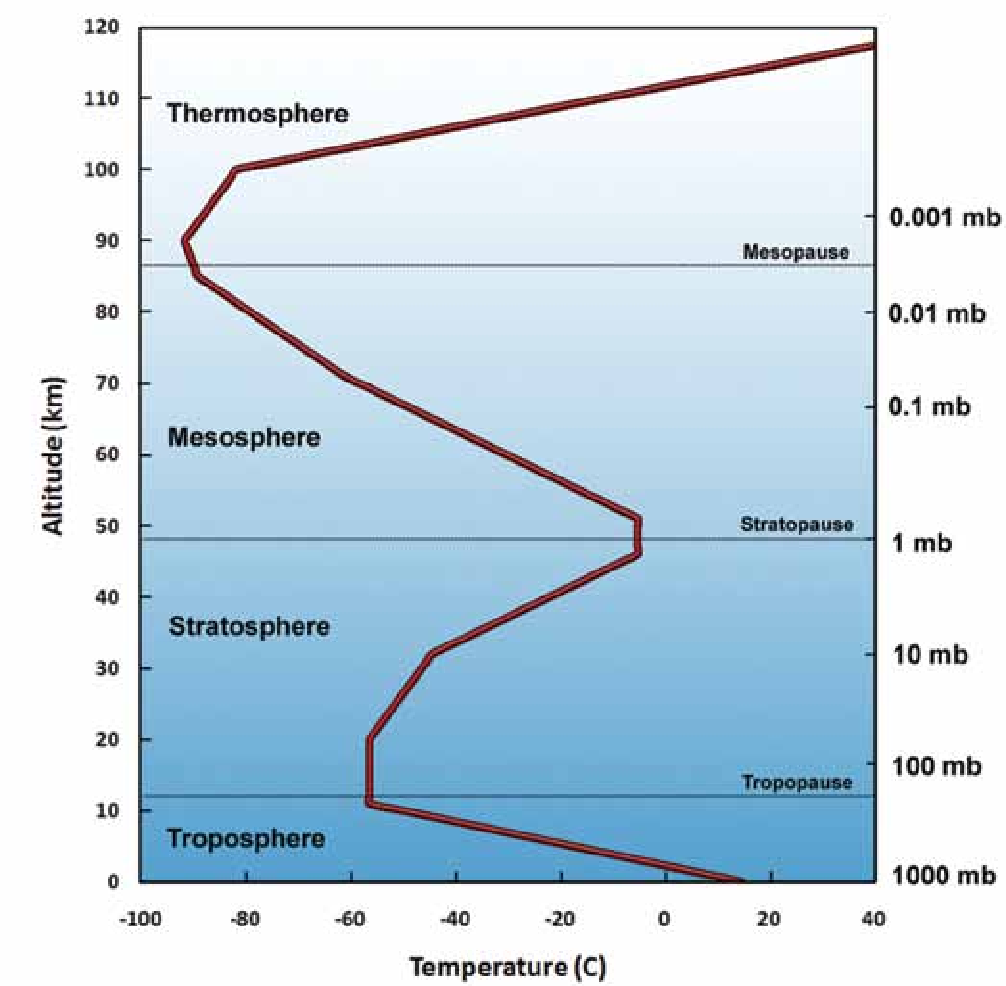
The Earth's atmosphere is primarily comprised of oxygen (21%) and nitrogen (78%). The remaining 1% is still very important to the Earth-atmosphere system because of its role in biological processes and interaction with the incoming solar and outgoing infrared radiation. Two scarce but important molecules are ozone, which absorbs ultraviolet light from the sun, and carbon dioxide, which absorbs infrared radiation and helps to regulate atmospheric temperature. By absorbing the Sun's ultraviolet radiation, ozone blocks these life destroying rays from reaching the Earth's surface. Without the trace gas ozone, the Earth might be uninhabitable.

Under normal temperatures, all of the atmospheric constituents are gases except water molecules which can be in solid (ice), liquid (cloud and rain droplets), and gaseous (water vapor) form. When water molecules change phase, heat is released to or absorbed from the atmosphere. This plays an important role in the formation of severe storms and tropical cyclones, as well as the general circulation – prevailing wind patterns – of the atmosphere. Water vapor is also the most important greenhouse gas – without it the Earth would be about 20 degrees Centigrade colder than it is now.

Most of the incoming solar radiation passes directly to the surface, heating the atmosphere from below. About 90% of the atmosphere is in the troposphere (see figure opposite page) where most of the weather with human impact occurs. The temperature increases with height in the stratosphere due to ultraviolet absorption by ozone and in the thermosphere because a small amount of energy absorption results in large temperature increases due to the very low density.

The atmosphere is heated more at the equator than at the poles because of the sun-Earth geometry, which provides the energy for the large-scale circulation patterns of the atmosphere and establishes the Earth's major climatic zones.

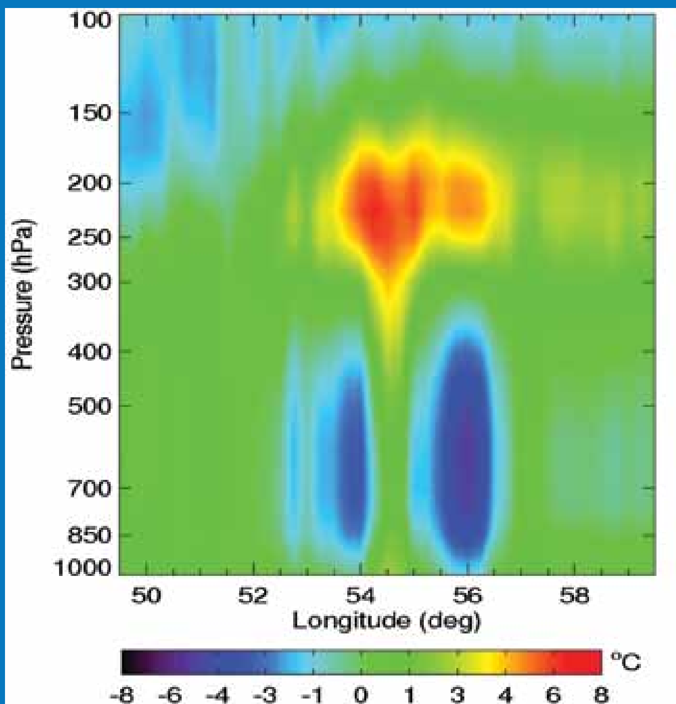
Temperature Change with Altitude



The average temperature of the atmosphere versus height. The right vertical axis is pressure measured in millibars. The atmosphere is divided into 4 layers (troposphere, stratosphere, mesosphere and thermosphere). The mass in an atmospheric layer is proportional to the pressure difference of the layer, which indicates that most of the atmospheric mass is in the troposphere.

Seeing Into the heart of a hurricane

A cross-section of Tropical Cyclone Giovanna (below) off the coast of Madagascar at 0630Z, February 13, 2012, reveals its internal temperature anomaly from the average temperature at each level as a function of altitude (pressure, vertical axis) and east longitude (horizontal axis). Note the high temperatures toward the upper central part of the storm. This warm region is caused by the release of latent heat as the water vapor drawn upward from surface condenses into cloud droplets. The colder areas in the lower part are due to radiational cooling caused by heavy rain. The temperatures are from the Suomi NPP Advanced Technology Microwave Sounder (ATMS).



Atmospheric Temperature Sounding

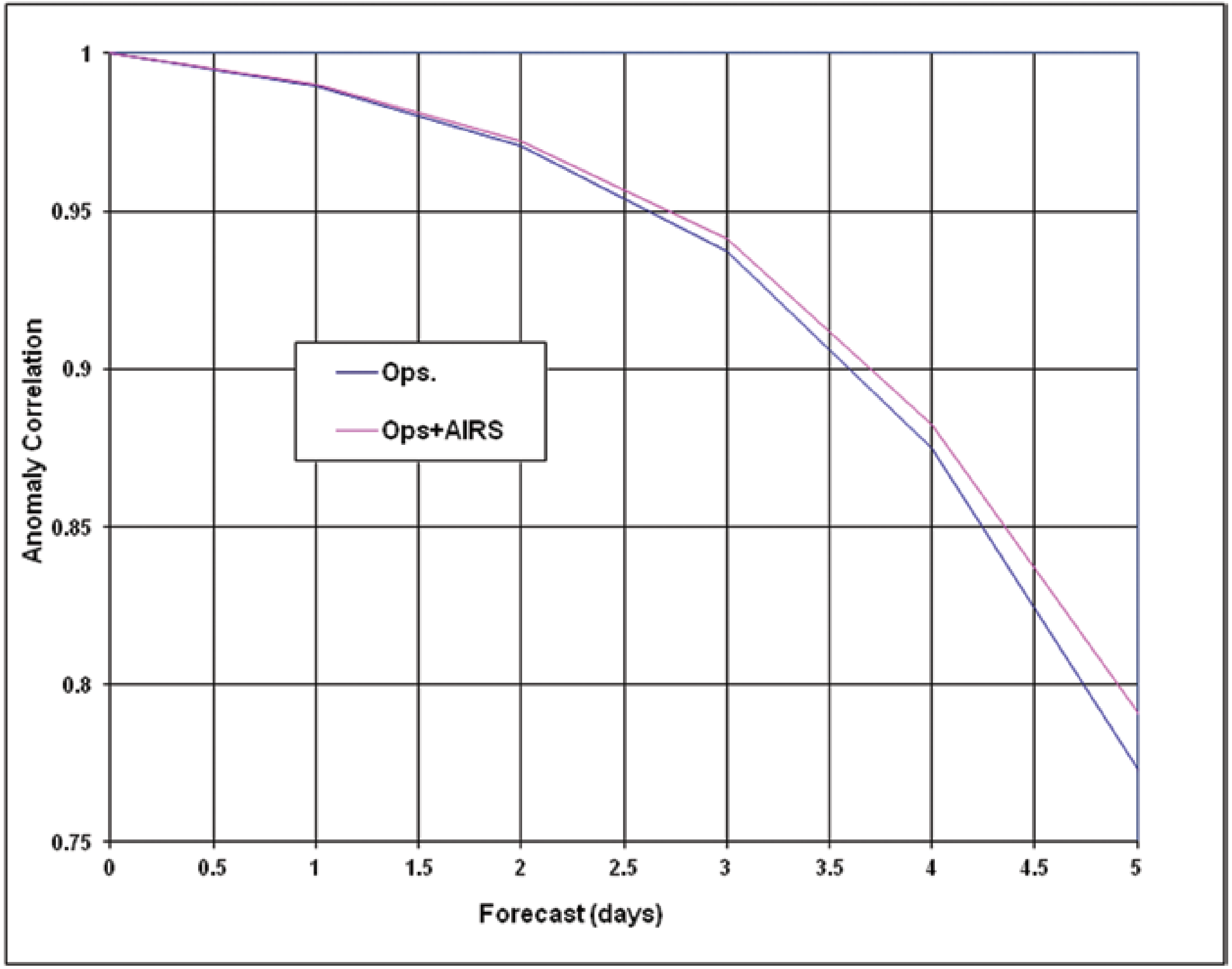
Lihang Zhou, Mitch Goldberg, Fuzhong Weng, and Tong Zhu

Imagine looking through the eye of a hurricane and knowing the storm structures from the inside out – that is something that today's satellite technology can do! Accurate observations of the three dimensional distribution of atmospheric temperature over the globe are critical for numerical weather prediction and climate studies. Satellite infrared or microwave instruments measure the radiation emitted by the atmosphere at different wavelengths (so called channels). Different channels are sensitive to the radiation emitted from the different altitudes of the atmosphere. The amount of emitted radiation depends on the temperatures at these altitudes. From a careful analysis of the radiance data observed by different channels and solving the radiative transfer equation, one can deduce the atmospheric temperature at different altitudes.

The atmospheric sounding channels are located in parts of the infrared (IR) and microwave spectrum for which the atmosphere is the main contributor to the measured radiance. Microwave sounders have the ability to see through cloud and hence offer nearly all-weather capability; but their spatial resolution is generally lower than that of the IR instruments.

The new generation of hyper-spectral sounders has advanced capabilities for atmospheric sounding. NASA's Atmospheric InfraRed Sounder (AIRS) is the first hyperspectral – thousands of spectral channels – instrument to be used operationally for weather forecasting. With 2378 spectral channels, AIRS has a spectral resolution more than 100 times greater than previous IR sounders, which enables retrievals with much improved vertical resolution. From 2002 to the present, STAR has been actively participating in the development of the AIRS products and has developed a retrieval system to process and distribute the high quality AIRS temperature, moisture and trace gas sounding products in near real time to National Weather Prediction centers worldwide.

Extending the Range of Accurate Weather Forecasts

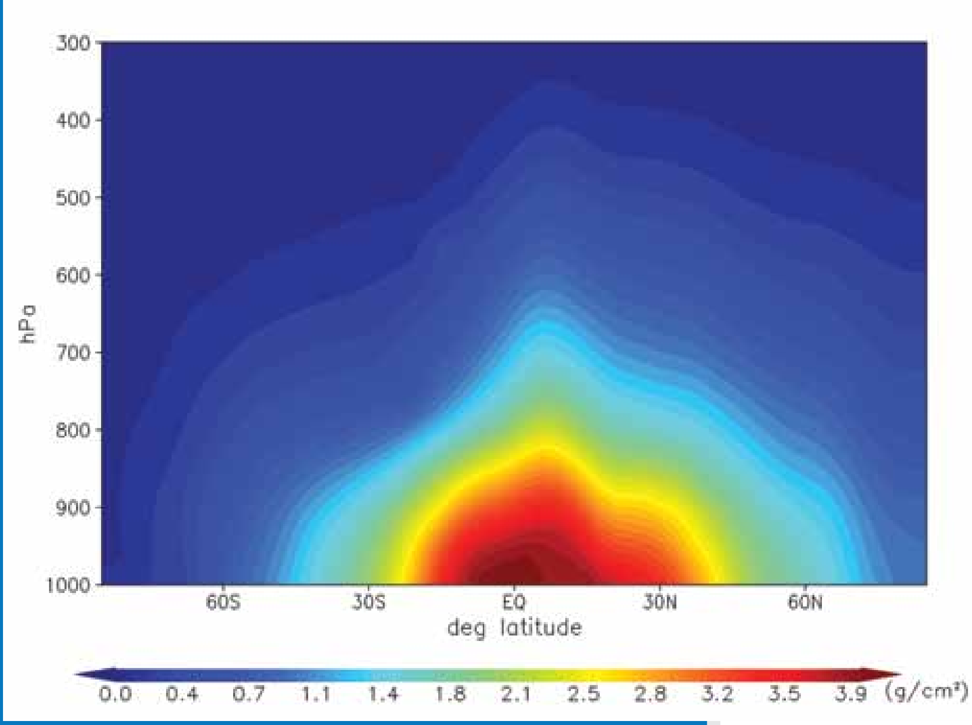


The first tests of the impact of a hyperspectral temperature sounder – NASA's Atmospheric InfraRed Sounder (AIRS) – on weather forecasts revealed significant increases in forecast skill in the Southern Hemisphere and improvements in the Northern Hemisphere. The figure shows the 500 mb anomaly correlation – a standard measure of forecast skill – for the Southern Hemisphere as it falls off with forecast duration. OPS represent the forecasts without the AIRS data, and OPS+AIRS includes assimilation of AIRS radiance observations. The increase in forecast skill at 5 days is equivalent to gaining a 5 hour extension of prediction capability. While this may seem small, it is quite significant when compared to the rate of general forecast improvement over the last decades: a 5 hour increase in forecast range normally takes several years of NWP model development to achieve. (Photo credit: NASA-NOAA-DOD Joint Center for Satellite Data Assimilation)

Water vapor retrieval from AIRS

The water vapor cross section below shows the vertical distribution of water vapor for different latitudes, from the equator to the poles, as observed by the Atmospheric Infrared Sounder. The Y-axis is the altitude in pressure units; X-axis is the latitude in degrees. The water vapor is the column precipitable water (vertically integrated water vapor in a column of atmosphere) in units of g/cm^2.

The high water vapor amounts in the tropics and very low values in polar regions are quite evident, as is the decrease of water vapor with altitude, which is especially rapid in the tropics.



Atmospheric Water Vapor Sounding

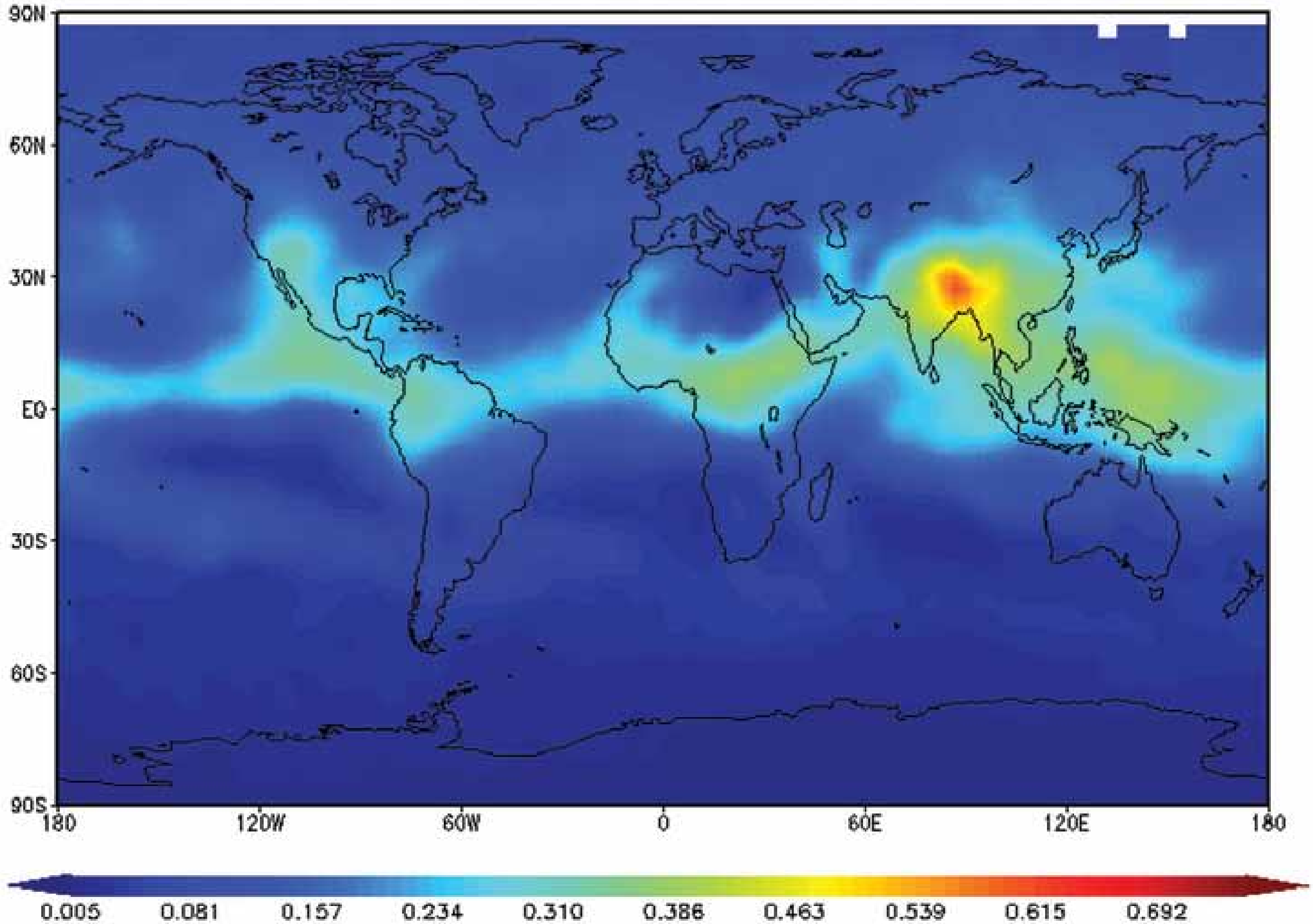
Lihang Zhou, Mitch Goldberg, Laurie Rokke, Walter Wolf, and Xingpin Liu

Water vapor plays a critical role in the transfer of energy and water in the atmosphere/ocean/land system. Satellite instruments measure the radiation emitted at wavelengths where water vapor is weakly and strongly absorbing in both the microwave and infrared spectral regions. The different wavelengths are sensitive to different layers of the atmosphere and the observed radiation depends on the temperature and water vapor content in these layers. Since the temperatures are known from the satellite temperature soundings, the water vapor profile can be retrieved.

STAR has developed several systems to generate and distribute operational water vapor products. The Advanced TIROS Operational Vertical Sounder (ATOVS) data processing system provides near real-time water vapor mixing ratios (the ratio of the amount of water compared to a dry gas) at 19 levels (from surface to 200 mb) with a 40 km horizontal resolution derived from the AMSU-A and HIRS measurements on board the NOAA polar orbiting and European Metop satellites series. The operational Microwave Integrated Retrieval System (MIRS) is an upgrade to the NESDIS operational microwave retrieval system known as MSPPS (Microwave Surface and Precipitation Products System) with the extended capability of providing atmospheric temperature and moisture profiles in all-weather conditions and over all-surface types.

The three dimensional global distribution of water vapor from the surface to the top of atmosphere has been obtained from the hyperspectral IR observations of AIRS since 2002 and the European Infrared Atmospheric Sounding Interferometer (IASI) since 2006. The narrow spectral channels and huge number of observing wavelengths provide increased vertical resolution, and minimize the sensitivity to interference signals. The more accurate water vapor retrievals with higher vertical resolution provide enhanced water vapor information for assimilation in NWP models and capture the long term variability and trend of the vertical structure of water vapor.

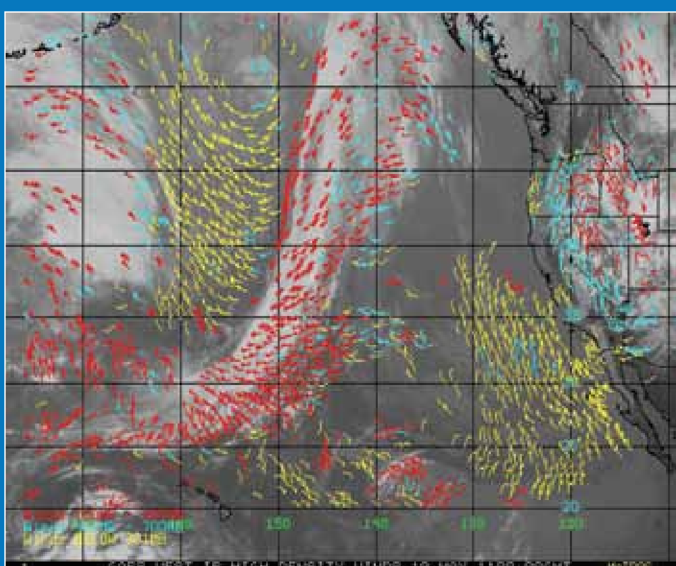
Global Map of Water Vapor in the Middle of the Atmosphere



Average water vapor amount (grams of water) in a 1-km layer at the 5-km level of the atmosphere for the month of July 2006. While most of the atmosphere is relatively dry at this level with only about 0.1 g of water vapor, the India monsoon area has about six times as much moisture. With its fine spectral resolution and large number of observing channels, the Atmospheric Infrared Sounder instrument (AIRS) enables measurement of water vapor at many levels in the atmosphere.

Cloud and moisture drifts reveal winds

Atmospheric winds at different levels in the atmosphere are derived by tracking the motion of clouds or moisture features over time. This is done using measurements from geostationary and polar orbiting satellites. The image shows winds in the Eastern Pacific derived from NOAA's GOES-11 satellite. Counter-clockwise circulation of low-level winds (shown by yellow wind barbs) clearly shows the position of a low pressure system located south-east of the Aleutian Islands and its associated cold front where upper-level winds (shown by red wind barbs) indicate the location and strength of the jet stream. Parts of the Western United States are being impacted by an upper and mid-level low pressure system as indicated by the counter-clockwise circulation upper (shown by red wind bards) and mid-level (shown by cyan wind barbs) winds. White areas are regions of cloudiness.



Winds

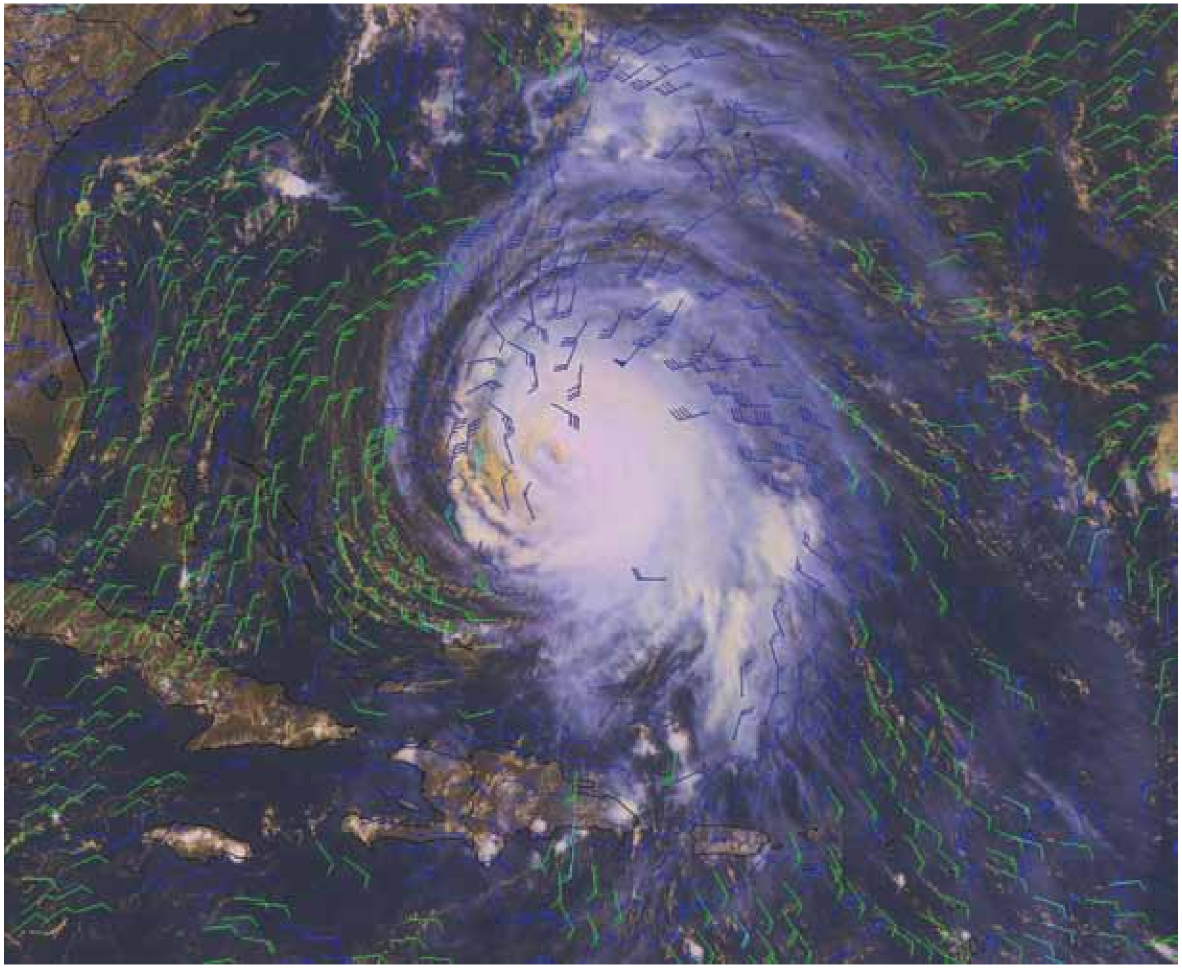
Jaime Daniels

Atmospheric winds derived from passive instruments aboard geostationary and polar satellites provide tropospheric wind information over the vast regions of the Earth without weather stations, including the oceans, tropics, Southern Hemisphere land masses, and Polar Regions. The satellite winds are assimilated into numerical weather prediction (NWP) models, where their use improves the skill of the weather forecasts and hurricane warnings. In addition, the satellite winds help meteorologists at weather stations around the country to make better local weather analyses and forecasts.

Winds were originally derived from satellite images by tracking drifting cloud systems on successive images. Techniques were then developed to track features in water vapor images (images constructed from measurements at a wavelength at which water vapor emits radiation). Developed for geostationary satellites with their frequent measurements, the techniques have recently been implemented for polar satellites. Polar orbiters pass over the poles about every 90 minutes, allowing winds to be derived from sequential images.

STAR scientists have developed the algorithms that enable the generation of atmospheric winds from a number of existing NOAA, NASA, and international satellites that include NOAA's GOES, NASA's polar orbiting Terra and Aqua, and the Japanese geostationary Multi-Functional Transport Satellite (MTSAT). They are now developing new and improved algorithms for the next generation of NOAA geostationary and polar satellites that include GOES-R, Suomi NPP, and JPSS.

Winds around Hurricane Isabel



GOES-12 cloud-drift winds derived over and in the vicinity of Hurricane Isabel on September 15, 2003. The wind barbs indicate the direction and speed of the derived wind as determined by measuring the motion of clouds in and around the hurricane. The wind barbs are color coded to indicate the height of the derived winds. Blue, cyan, and green wind barbs indicate that the winds are 7-14 km, 3-7 km, and 1-3 km high in the atmosphere, respectively. Note how the low-level counterclockwise inflow into the hurricane changes to a clockwise outflow at upper levels (compare the direction of the green arrows versus the blue arrows around the hurricane).

Examining clouds from space

Is there a cloud? 12 different tests that exploit the spectral, spatial and temporal characteristics that make clouds appear distinct from clear conditions are applied. For example, clouds are brighter, colder, and more patchy than the clear background.

Water or ice cloud? IR observations at several wavelengths are used to separate ice and water clouds, since they have different radiative emission properties.

At what altitude is the cloud? IR observations at three wavelengths are used to estimate the height and microphysics of the highest clouds. Basically, the observed IR radiation depends on the cloud temperature, which can be converted to cloud height if one knows how the temperature varies with altitude.

How much water is in the cloud? Cloud Optical Properties, which can be converted to cloud water amount, are determined by analyzing the spectral variation of cloud brightness and emitted IR radiation.

Swirls of clouds resulting from the interaction of the atmospheric flow and the topographical features of the Cape Verde Islands, as seen from the Space Shuttle. (Photo credit: Astronaut Don Pettit/NASA)

Cloud Properties

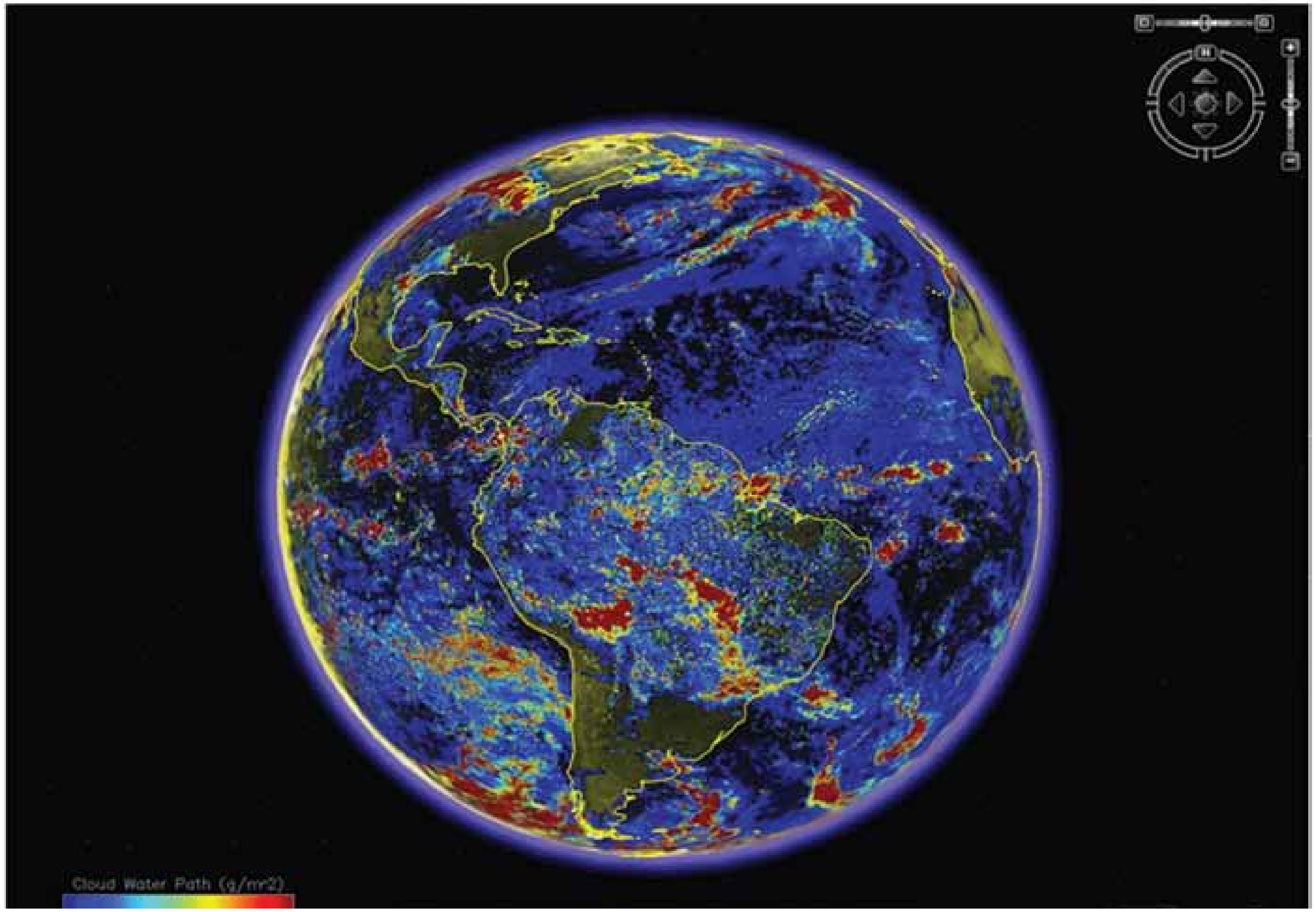
Andrew Heidinger and Andi Walther

When the Earth is viewed from space, the most dominant feature is its cloud cover – typically about 70% of the Earth's surface is covered by cloud at any one time. Clouds are important modulators of radiation, play significant roles in the hydrological cycle, and provide important insights into the dynamical structure of the atmosphere.

STAR scientists are preparing a suite of products to provide advanced capabilities for cloud detection and retrieval of cloud properties. The Team has developed five algorithms to generate ten unique cloud products for the Advanced Baseline Imager instrument that will fly on the next generation NOAA geostationary satellite – GOES-R. Versions of these algorithms have been developed for all of the current and future NOAA satellite imagers including the Visible and Infra-red Imager on the next generation NOAA polar orbiting satellite – the Joint Polar Satellite System. The enhanced resolution and additional spectral channels provided by the future sensors will offer new opportunities for remote sensing, providing more accurate measurements of cloud location, cloud type and phase, and cloud top properties. Recent advancements in radiative transfer and ancillary data have also led to significant improvements of the cloud properties derived from the current instrument suite.

STAR has access to measurements from NASA's advanced active remote sensing cloud instruments. The lidar and radar (light and radio detection and ranging) observations of cloud vertical structure from the NASA Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO) and CloudSat missions have greatly improved STAR's efforts to validate and characterize its cloud products from the passive NOAA satellite instrument observations.

Cloud Water Amount



Map of cloud water path – the amount of water in a vertical column of cloud – as determined by the Daytime STAR'S Cloud Optical and Microphysical Properties algorithm. The observations are from the GOES-12 imager on day 90 of 2010 at 17:45 UTC.   Note the particularly high water amounts (yellow and red areas) in the cloud systems of the equatorial oceans, the strong convective regions of Brazil and Bolivia, and the mid-latitudinal storm system in the Atlantic Ocean. Cloud water path is a critical variable because it provides information on how clouds impact the hydrological cycle and the Earth's radiation budget.

Water vapor, clouds, precipitation, and atmospheric rivers

Where does our water vapor come from?
The primary source of water vapor is evaporation from the ocean and other large water bodies. Evaporation also occurs over land, but to a much lesser extent. The water vapor evaporated into the atmosphere is transported around the globe by wind.

How is water vapor related to precipitation?
The warmer the atmosphere, the more water it can hold before it will become saturated and condensation begins (i.e., water goes from gas to a liquid form). Meteorological conditions that lead to rising air ultimately yield clouds – collections of water and ice particles – which, with sufficient water vapor, grow and produce rain and snow when the particles become too large to stay suspended in the atmosphere. Because the atmosphere is warmer in summer than in winter, most intense precipitation events occur in the summer. The atmospheric river (a long, relatively narrow plume of moist air) is an efficient process that helps sustain the development of clouds and precipitation; when a river is captured by a slow-moving storm system, the precipitation falls in a long duration event that leads to flooding episodes.

Where and when are atmospheric rivers most prevalent in the U.S?
Along the west coast of the U.S., atmospheric rivers occur mostly in the fall and winter seasons. In the eastern U.S., they can occur any time of the year; however, the most extreme instances are in the summer and fall when rivers emanate from Atlantic Hurricanes.

Amazon Rivers in the Sky

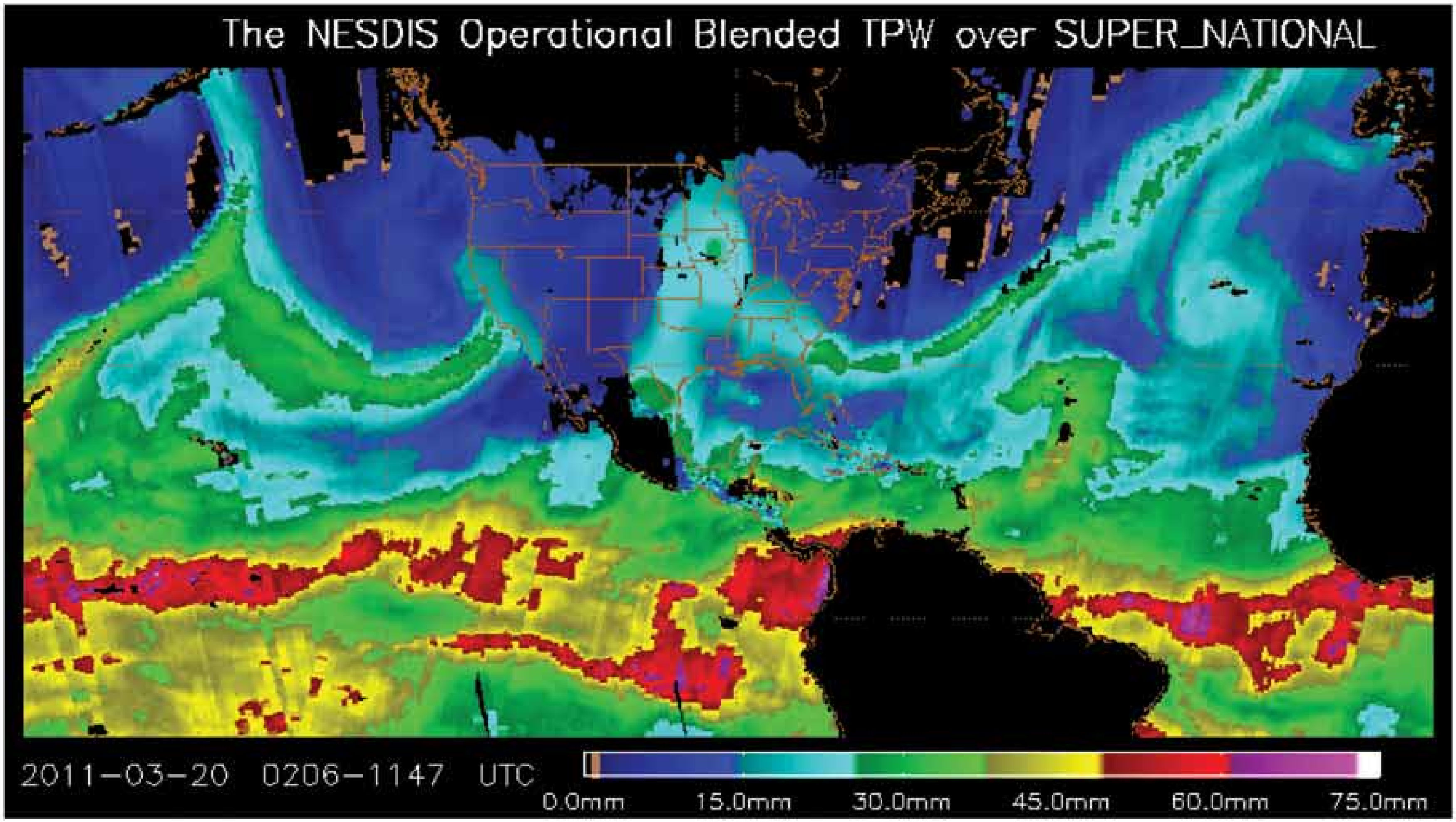
Ralph Ferraro, Mark DeMaria, Stan Kidder, and John Forsythe

Flooding affects more people worldwide than any other naturally occurring high-impact phenomenon. Our ability to predict and monitor the occurrence, location and duration of precipitation events cannot be accomplished without weather satellites; they provide forecasters with a global view of evolving atmospheric conditions related to flood producing storms.

The Earth's atmosphere is very efficient in transporting water in gaseous form (referred to as "water vapor", "atmospheric moisture", and "precipitable water") that contributes to rain and snow. Most of this moisture is concentrated in the atmospheric layer from the surface to around 10,000 feet. When prolonged and heavy rainfall events occur, there is usually an "atmospheric river" associated with them – it is a long (hundreds to a thousand miles), relatively narrow (a hundred miles or so) plume of moist air that feeds into a weather system to sustain and enhance the precipitation associated with it. The river will typically focus itself on a particular region, prolonging the duration of the event. The rivers generally originate in tropical zones and extend to the mid-latitude areas of North America and Europe. It has been calculated that the amount of water vapor transported by an atmospheric river is on the same order as the discharge from the Amazon River, which is over 4000 miles long!

Satellite instruments, primarily passive microwave sensors that are flown on NOAA, NASA and Department of Defense satellites, can accurately measure this water vapor so that the atmospheric rivers can be mapped and tracked around the globe. Scientists from STAR and its Cooperative Institute partner at Colorado State University have recently developed a "blended" product, which incorporates all available satellite and, over the U.S., ground-based GPS water vapor measurements into a single composited image of global moisture. This product vastly improves a weather forecaster's ability to monitor and predict heavy, long duration precipitation events (see figure).

Blended Total Precipitable Water and Atmospheric Rivers



An example of NOAA's Blended Total Precipitable Water product for the time period 0206 – 1147 UTC on 20 March 2011. It consists of measurements from several U.S. and European satellites, integrated into a single product for easier use by NOAA weather forecasters. The colors represent different levels of moisture as indicated by the color bar below (units are in mm). Over the U.S., ground measurements are integrated with the satellite product. At this time, a long duration precipitation event was occurring over California; note the "river" of moisture (green) extending across the Pacific Ocean and targeting the California region.

Worldwide use of satellite rainfall data

U.S. National Weather Service forecasters use estimates of rainfall from satellite data to supplement radar and rain gauge information, especially in regions where radar coverage is lacking – for instance, in the Rio Grande River region where heavy rains in Mexico can cause significant flooding but go undetected by the U.S. radar network.

Forecasters in other parts of the world find even greater value in satellite-based estimates of rainfall since radar and rain gauge data are less readily available. Weather services in Mexico, Brazil, and South Africa are running their own versions of the operational U.S. rainfall algorithm. Also, a partnership among NOAA, the World Meteorological Organization, and a private nonprofit organization is working to implement a real-time flash flood forecast system that uses rainfall estimates from satellites. Forecasters in Central America, southern Africa, Southeast Asia, and parts of the Middle East are benefiting from this information, which will result in better warnings of flash floods and fewer fatalities.

STAR scientist Bob Kuligowski lectures at the Korean weather service on techniques for measuring rainfall from satellites.

Precipitation and Flash Floods

Robert J. Kuligowski

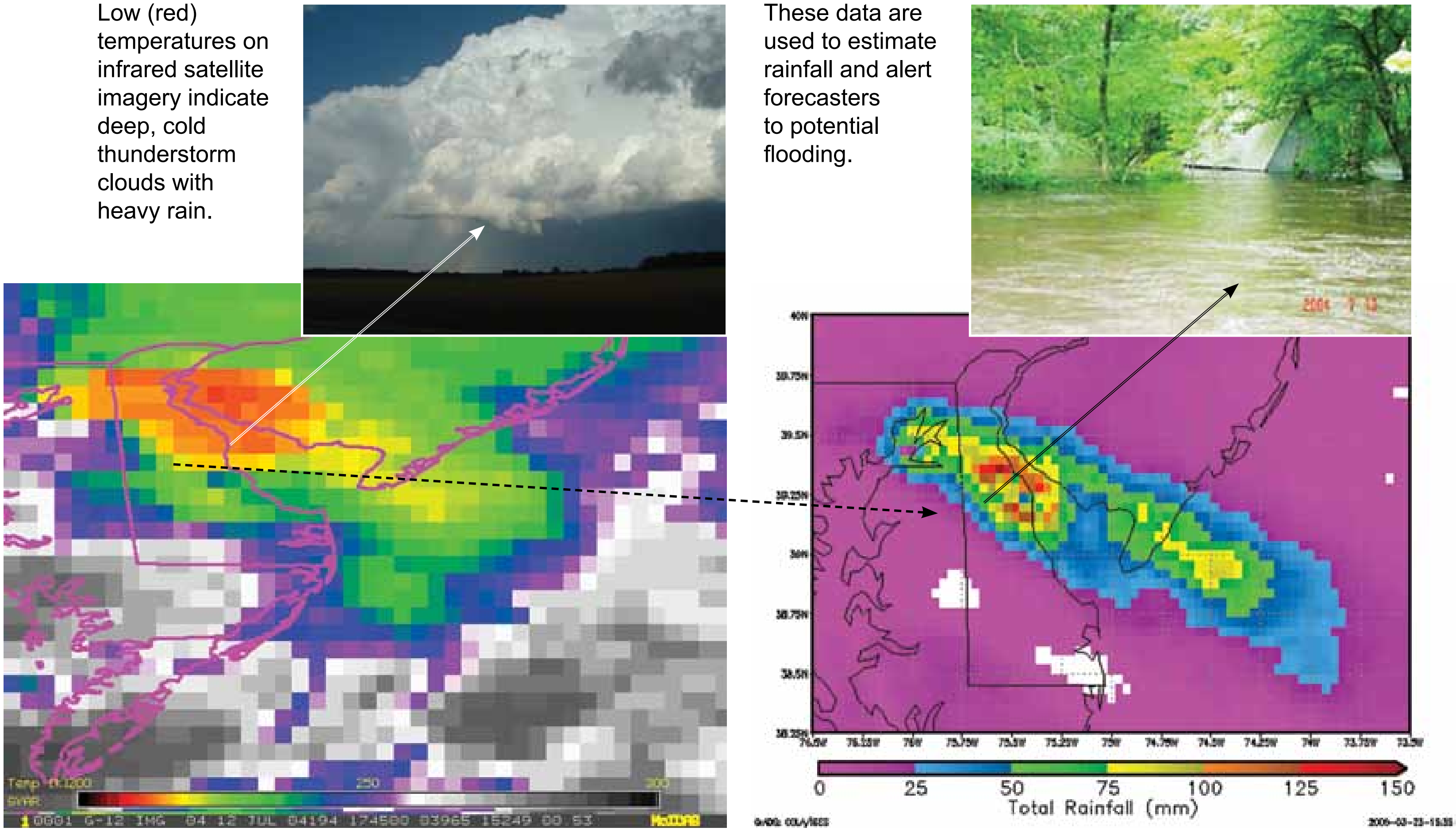
Floods are one of the most costly natural disasters in the world – according to the United Nations International Flood Initiative, they affect an average of 520 million people each year, with 25,000 deaths and $50-60 billon in damages. Floods have a variety of causes (dam breaks, melting snow, tidal surges), but many are the result of excessively heavy rain during a very short period of time.

Weather forecasters often use rain gauges and radar to detect flood-producing heavy rain, but both have limitations: rain gauges are usually spaced too far apart to detect smaller storms, and weather radars are not available in many parts of the world.

Data from satellites, however, cover the entire globe, and weather forecasters have used space observations to monitor rainfall since the 1970s. Manual techniques have been replaced by automated programs that can compute rainfall estimates for the entire globe in a matter of minutes. Speed is essential to warn people who are in the path of a rapidly-evolving flash flood.

The earliest methods for estimating rainfall relied on estimates of cloud-top temperature (thick clouds, which produce rain, extend high into the atmosphere and have low cloud-top temperatures) from infrared sensors on geostationary satellites. More accurate estimates can be obtained using microwave observations (at certain wavelengths, they are sensitive to the radiation scattered by rain drops), but these measurements are available only from polar orbiting satellites that provide updated information only a few times per day. STAR scientists are researching how best to combine these two sources of data to provide the best possible rainfall estimates for forecasters.

Flash Floods from Space



GOES-12 infrared image from 12:45 PM EDT 12 July 2004.

Satellite-based total rainfall from 11 AM-7 PM EDT 12 July 2004

An illustration of the process of estimating rainfall from infrared satellite data from a case of heavy rain and flash flooding over Delaware and southern New Jersey. Colder cloud tops are assumed to have stronger updrafts transporting moisture upward, and thus heavier rates of rainfall production. (Photo credits: NOAA/Tracy Felty (upper left); USGS (upper right))

What do forecasters say?

During a National Weather Service (NWS) Assessment of the operational value of the GOES Sounder products, forecasters said that the Sounder products provided valuable information, often indicating temporal and spatial gradients unavailable from any other source. Forecasters indicated that in 79% of the active weather situations considered, the GOES Sounder products led to improved forecasts.

Selected quotes from forecasters:

Tornado warning, Minneapolis, MN:

"The Sounder Derived Product Imagery (DPI) helped a lot in anticipating convective development over southern MN this evening."

Flash flood warning, Grand Junction, CO:

"Edge of cloud shield revealed significantly higher Total Precipitable Water (TPW) values over … our forecast area. Based on the TPW and [other data] issued flash flood warning." (Photo credit: NOAA)

Atmospheric Instability: Signaling Extreme Weather

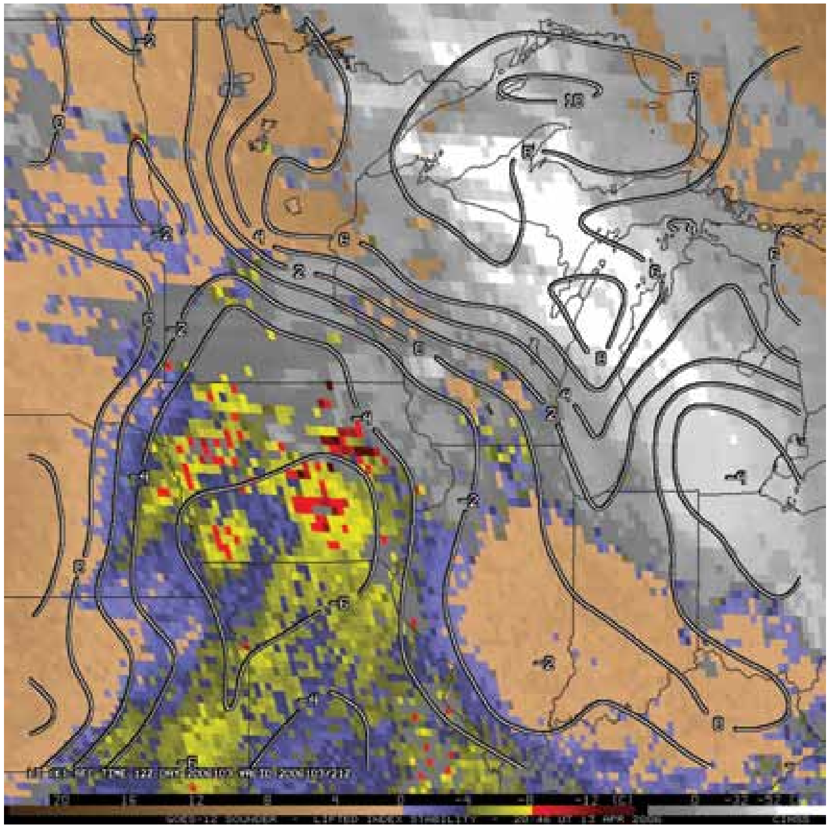
Timothy J. Schmit and Gary S. Wade

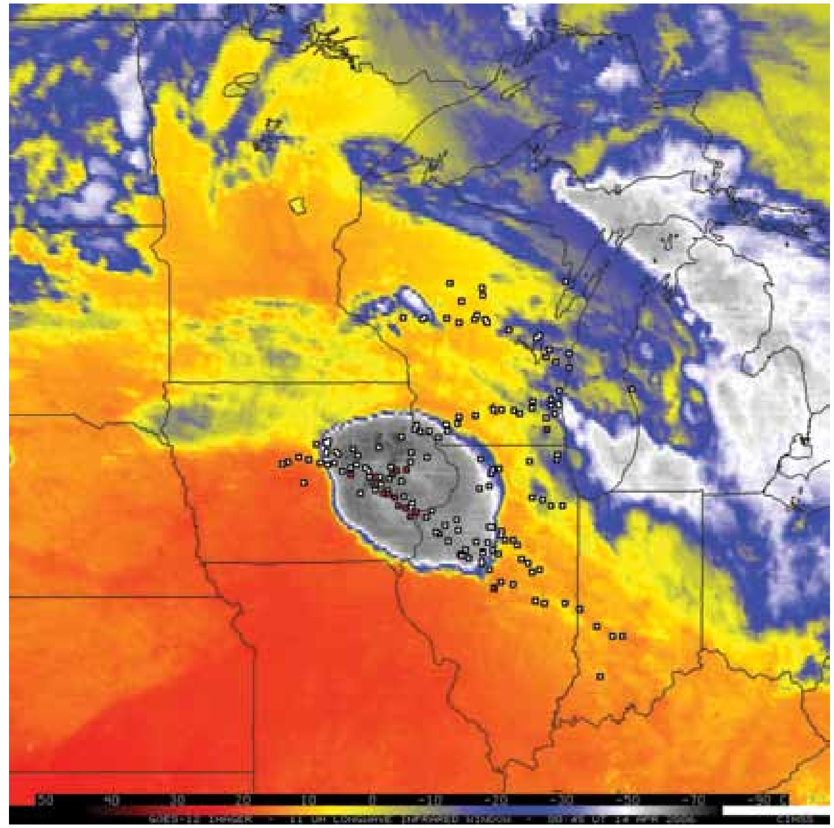
Forecasting high impact weather events such as severe thunderstorms and tornadoes is extremely difficult. Compared to the large scale mid-latitude storms that develop and grow relatively slowly – and last for days as they move across the country – thunderstorms and tornadoes are small, develop quickly, and do their damage within a few hours. Current numerical weather prediction models are not up to the job of predicting these events very accurately.

Thunderstorms and tornadoes are likely to form in regions of atmospheric instability. In such regions, a parcel of rising air becomes less dense than its environment as a result of the release of latent heat as clouds form. Being lighter than the surrounding air, the parcel continues to rise. This unstable situation can produce convective cells that have the potential to develop into severe weather. The Lifted Index (LI) is an indicator of atmospheric instability. It can be derived from GOES Sounder observations and represents the temperature difference between the actual air at 500 hPa (about 5 km) and that of an idealized "parcel" lifted to that level. Negative values of LI indicate instability.

In addition to the Lifted Index, a suite of other products from the GOES Sounder – Total Precipitable Water (TPW) (the amount of moisture that would be produced if all the water vapor in an atmospheric column were converted to liquid), cloud-top pressure, and effective cloud amount – is generated operationally in the form of Derived Product Images (DPI). These hourly images are displayed and animated within the National Weather Service visualization system – AWIPS, the Advanced Weather Interactive Processing System – for use by NWS Weather Forecast Offices across the country. The LI and the other DPI products enable forecasters to maintain a critical eye on rapidly developing severe weather conditions and issue timely warnings.

GOES Lifted Index Predicts Severe Weather





Left: Derived product imagery (DPI) of Lifted Index (LI) stability derived from the GOES-12 Sounder at 2046 UTC on 13 April 2006. The most unstable air (yellow to red areas) is across east central Iowa. Clouds are shown in shades of gray. Overlaid is the NWS model forecast (isopleths) of LI for the same time; the NWP maximum instability is over the western border of Missouri and Iowa. The image to the right shows that the most severe weather developed much closer to the LI maximum instability area than to the NWP forecast.

Right: GOES-12 IR image at 0045 UTC on 14 Apr 2006. A strong convective complex (gray area) with very cold cloud tops (-60 F or less) is evident over east Iowa and northwest Illinois. Severe weather reports from the NOAA Storm Prediction Center (SPC), for the evening of 13-14 April 2006, are overlaid (red=tornado; white=hail; light blue=damaging wind). The convection is seen to have first developed in the area of the most unstable GOES Sounder LI DPI (left image).

Tornadoes in 2011

By all accounts, 2011 was a historic year for tornadoes in the U.S. By the end of September, there had been 1784 reported tornadoes, placing the year among the most active tornado years on record. Associated with these storms, there were 546 fatalities, the third highest since collection of data began in 1875, and the most in one year since 1936.

The strength of tornadoes is measured by the Enhanced Fujita Scale, which ranges from 0 to 5, with an EF-5 having wind gusts exceeding 200 mph. A single tornado (rated EF-5) devastated the town of Joplin, Missouri, on May 22, killing 159 people, making it the deadliest storm since 1947 and the 7th deadliest on record. The most active single day during 2011 was April 27, when a total of 292 tornadoes were reported in the southeast and eastern U.S. Eleven of these were classified EF-4 – 166 to 200 mph – and four were rated EF-5. A total of 316 people were killed on April 27.

Damage from F5 tornado that struck Joplin, MO on May 22, 2011. (Photo credit: NOAA/NWS)

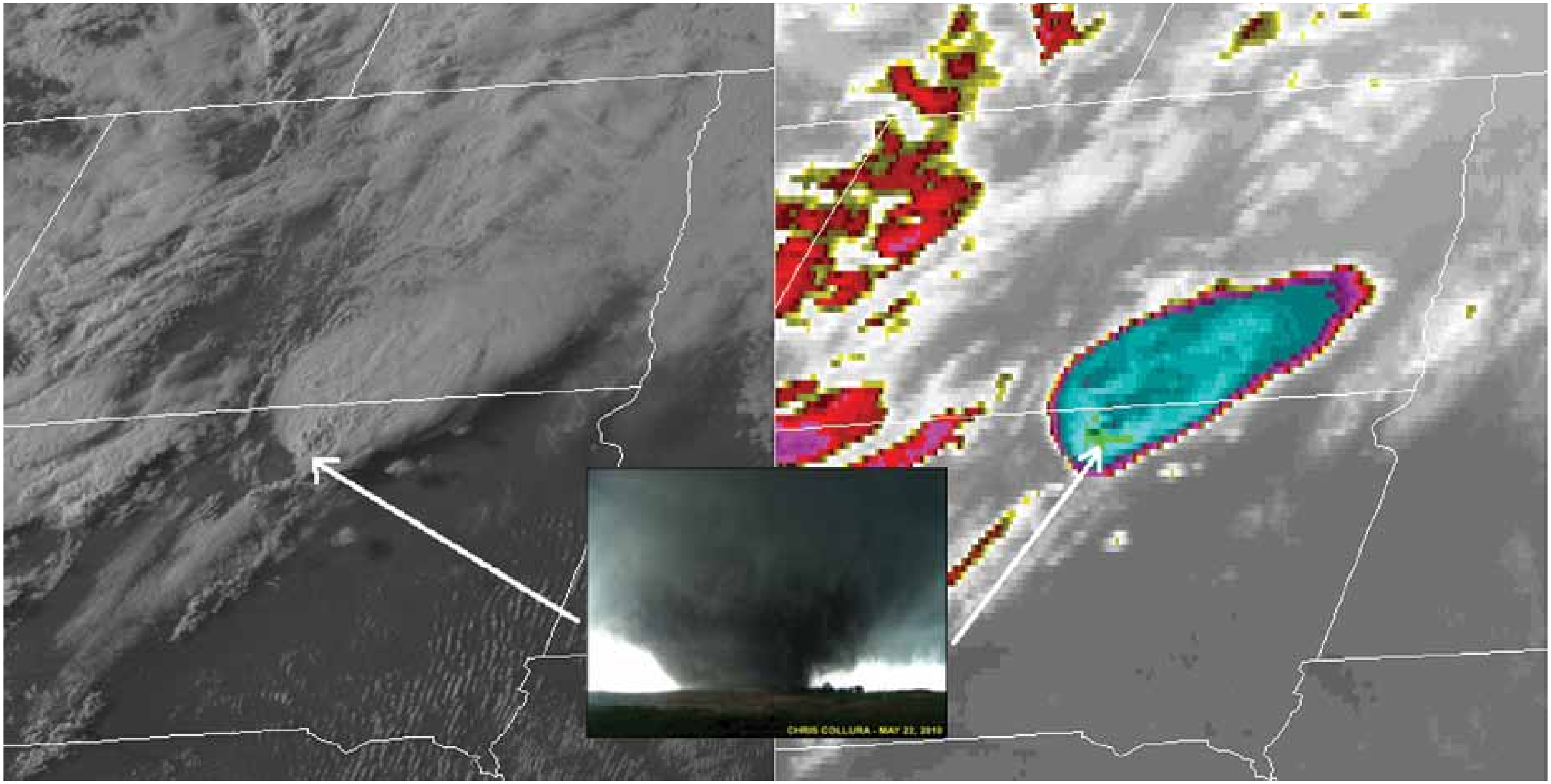
Thunderstorms and Tornadoes

Daniel T. Lindsey

Thunderstorms occur almost everywhere on the Earth at virtually any time of year, but the strength and type of storms vary greatly. Stronger storms may produce intense lightning, flash flooding, large hail, damaging winds, and, sometimes, tornadoes. The necessary ingredients for thunderstorm formation – sufficient low-level water vapor, an unstable atmosphere, and a "trigger" mechanism – are most common in the spring and summer in the U.S. The Gulf of Mexico is the primary source for low-level water vapor, and as this high humidity air moves north across the Central Plains, it encounters dry, unstable air aloft, resulting in strong, and sometimes violent storms. Vertical wind shear, or the change of wind with height, is another important factor that helps determine how storms organize. In general, more wind shear results in stronger storms, and wind shear in the lowest 3 km above the Earth's surface is particularly important for the formation of tornadoes. "Tornado alley," or the region from Central Texas northward to central Nebraska, gets its name from the frequency of large, damaging tornadoes. These potentially catastrophic events most often spawn from supercell storms, or isolated storms that have a rotating updraft.

In the U.S., where the coverage of ground-based Doppler radar is good, forecasters most often use geostationary satellite image sequences to locate regions where thunderstorms are starting to form, and then radar to issue warnings. But in mountainous regions or especially other countries, satellite imagery is the only source of information on storm strength. Visible imagery is used during the day, and infrared imagery, which also provides information about the vertical extent of storms, is used day and night.

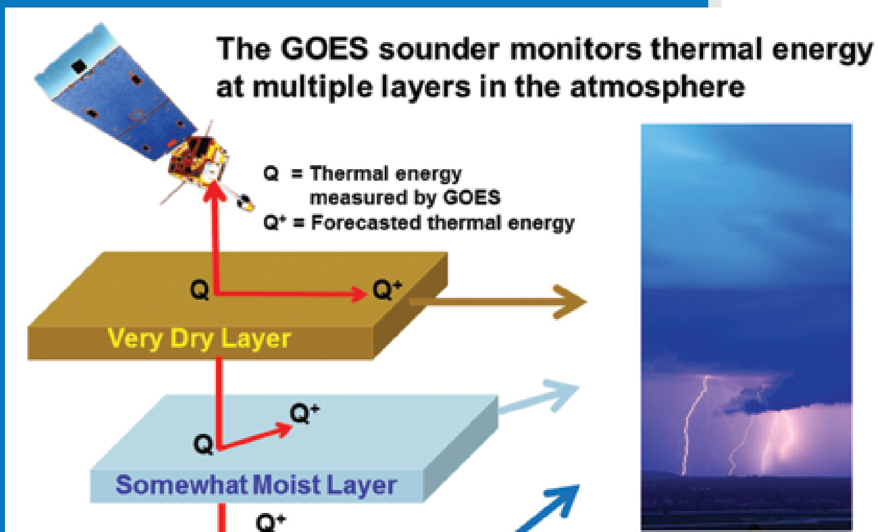
Supercell Thunderstorm



GOES-13 Visible (left) and color-enhanced Infrared (right) imagery from 22 May 2010 at 2345 UTC showing a supercell thunderstorm over northern South Dakota. Visible imagery is useful for locating key thunderstorm markers (overshooting tops, outflow boundaries, and flanking lines). The infrared imagery provides information on storm vertical extent and cloud top temperatures. This particular storm's top had a temperature of -67 °C and probably extended into the lower stratosphere. The photo in the middle shows a large tornado associated with this supercell at the same time as the GOES imagery, and the approximate location of the tornado is shown with the white arrows. The tornado was rated EF-4 (wind gusts 166 to 200 mph) on the enhanced Fujita scale, but luckily remained mostly over open country. (Photo credit: Chris Collura (center image))

Thunderstorm formation

Thunderstorms form when warm moist low level air moves under dryer air aloft. Air parcels near the surface become buoyant and begin to rise. Cloud formation produces additional warming, causing the parcel to accelerate upward, eventually forming a thunderstorm. The GOES Sounder can measure the temperature and moisture – the thermal energy – in these layers prior to the formation of clouds. Predicted winds are used to move the thermal energy forward in time at each level, as shown below. Areas favorable for thunderstorm development can then be identified in advance, as illustrated on the opposite page.



When layers with different thermal energy move in this manner conditions become favorable for strong thunderstorms.

Bridging the Gap: Nearcasting

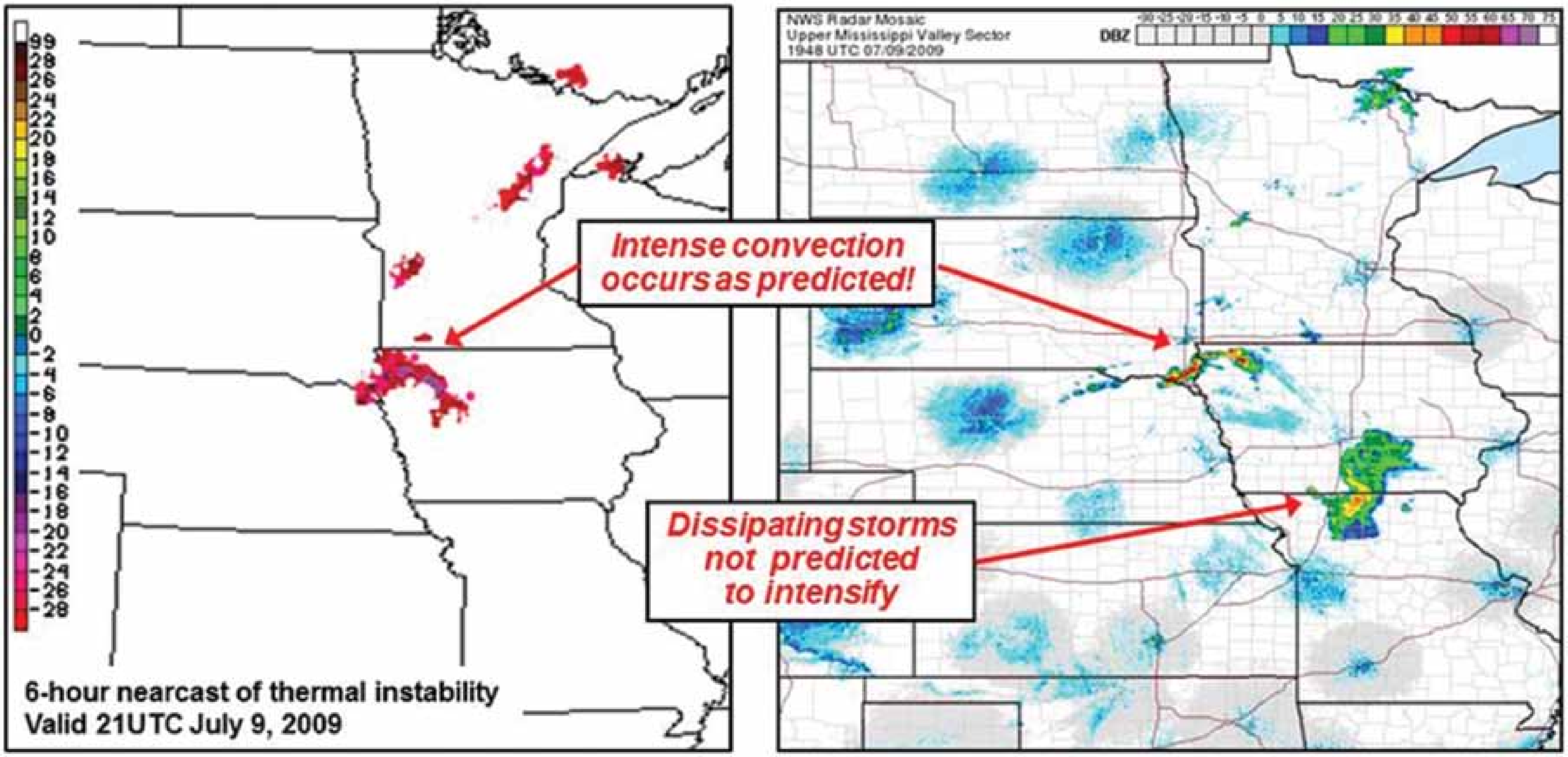
Robert Aune and Ralph Petersen

A serious gap exists in the guidance, based on nowcasts or predictions, that forecasters rely on to assess the potential for severe weather such as strong thunderstorms and tornadoes. Operational nowcasts are based on real-time radar and GOES imager observations that provide a snapshot of current conditions, but do not necessarily indicate what will happen in the next three to six hours. Numerical weather prediction (NWP) models are apt to contain erroneous perturbations in the first 6 to 12 hours that may incorrectly activate severe weather processes within the model. NWP models typically need to process forecasts out to 18 hours before these perturbations are systematically damped. NWP models also tend to smooth out the sharp horizontal changes in temperature and moisture where thunderstorms often form. This leads to errors in the timing and location of severe weather.

To close this gap, STAR has developed an innovative nearcasting system. The 18-channel infrared sounder on GOES measures temperatures and dew points at multiple layers in the atmosphere at locations 10 to 14 kilometers apart on an hourly basis across most of the United States. These measurements are converted by NESDIS into atmospheric instability indicators that are useful to forecasters for delineating areas where thunderstorms are likely to form. But, in the 20 to 40 minutes needed to process and transmit the information to forecasters, conditions may have changed. STAR scientists have developed a method that projects these stability indicators at multiple levels forward in time on trajectories driven by the predicted winds. The projected sounder observations are then re-examined to identify areas of maximum de-stabilization in the atmosphere. This approach has shown skill at identifying areas of severe weather potential out to 6 hours, thus filling the guidance gap.

Since the nearcasting model is relatively simple and very efficient, it can quickly provide hourly guidance to the field forecasters when they need it, leading to more accurate and timely severe storm warnings and forecasts.

Predicting a Strong Line of Thunderstorms



6-hour nearcast (left) of the thermal energy profile measured by the GOES-13 Sounder valid 21UTC, July 9, 2009. Red areas indicate that the thermal energy profile is favorable for thunderstorm development. The National Weather Service radar (right) indicates a strong line of thunderstorms has formed along the arc of thermal instability as predicted by the GOES Sounder Nearcaster. The area of storms in southern Iowa was dissipating at this time, verifying the Nearcaster prediction that these storms would not intensify.

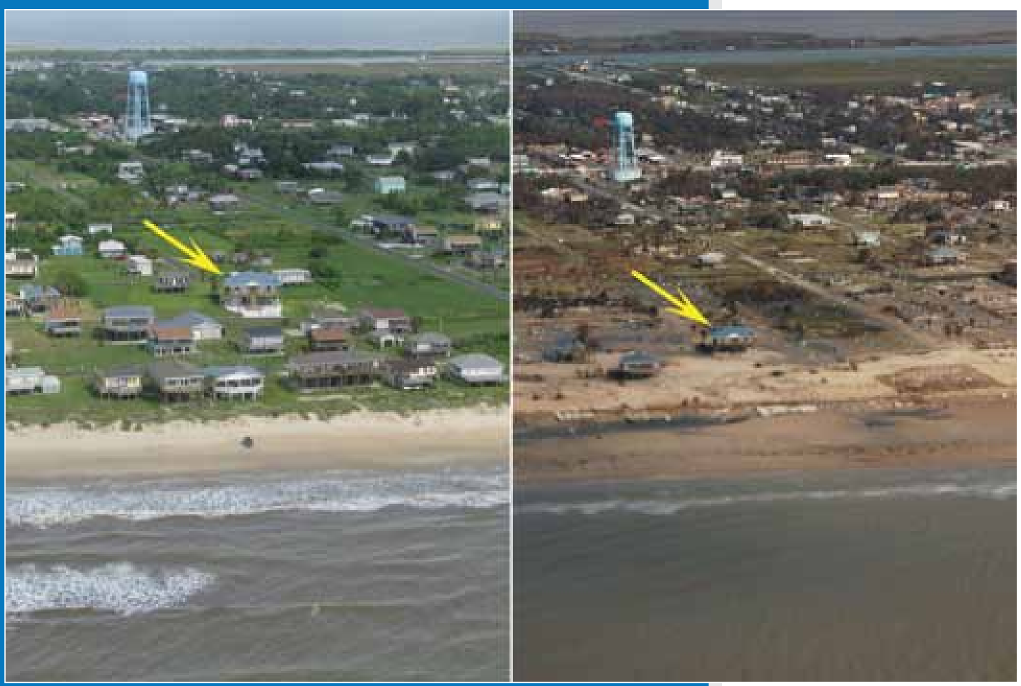
Tropical Cyclones

John A. Knaff

The primary energy source for tropical cyclones is the vast heat energy stored in the oceans in late summer and early fall. Common regional names for these low pressure systems include hurricane (in the North Atlantic and eastern North Pacific), typhoon (in the western North Pacific) and tropical cyclone. What makes tropical cyclones exceptional is that their strongest winds – up to 200 miles per hour – occur near the surface rather than at higher altitudes as with other low pressure systems. They are also large: the areas of damaging winds and heavy rainfall sometimes exceed 250,000 km^2. Because wind-related damage and storm surge are related to the size and strength of the wind field, these ferocious systems are considered the most dangerous and destructive of all storms.

Over 100 deaths, $25 billion damage

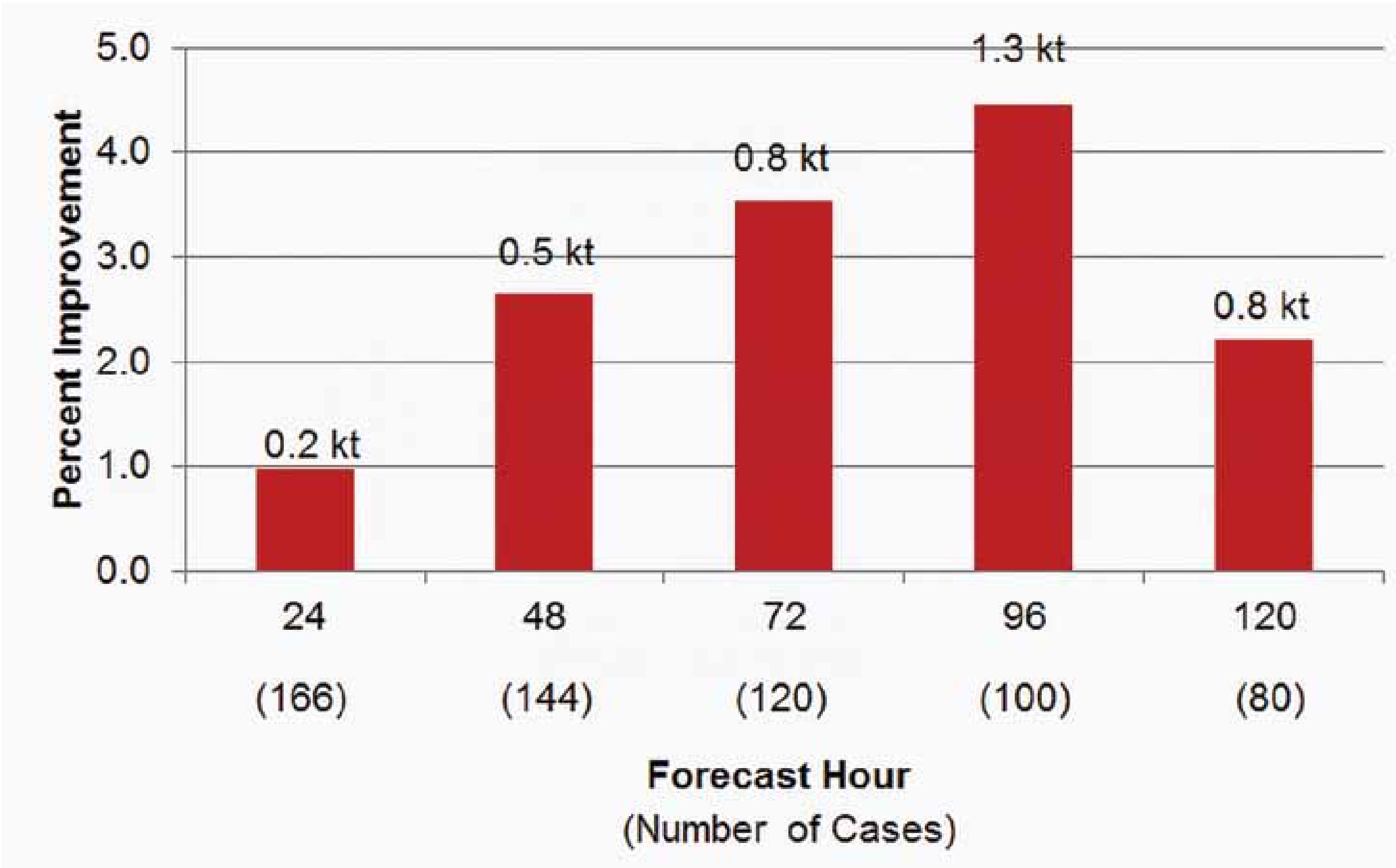
Ike, the third most costly U.S. hurricane, tracked across the northern Caribbean in 2008, and slammed parts of the United States Gulf Coast. It was directly responsible for over a hundred deaths and widespread damage from strong winds, storm surge, and inland flooding across Hispaniola, Cuba, the Turks and Caicos Islands, the Bahamas and Florida, Louisiana, and Texas. After landfall, additional deaths and significant damage occurred across parts of the Ohio Valley and southeastern Canada as the remnants of the storm moved through those areas.



Before and after image of the Bolivar Peninsula, Texas. (Photo credit: U.S. Geological Survey)

Tropical storms generally develop and intensify in remote oceanic regions, and satellite observations are universally used to estimate tropical cyclone location and motion, intensity and associated wind fields, cloud structures, rainfall rates and environmental conditions – information that is fed into models that provide storm track and intensity forecasts. STAR scientists have developed, and continue to improve, the Statistical Hurricane Intensity Prediction Scheme (SHIPS), an empirical model used by the National Hurricane Center as one of its tools for predicting hurricane intensity. A key input to SHIPS is satellite altimetry measurements, which provide information on ocean heat content. Use of the SHIPS model leads to significant improvements – up to 5 % – in forecasting the intensity, or strength, of these systems (see figure). Forecasts of hurricane intensity – as opposed to hurricane track forecasts – are extremely difficult, and improving intensity forecasts (by 20% in ten years) is a high priority of NOAA's Hurricane Forecast Improvement Program. Such advances will result in longer forecast lead times and ultimately reduce evacuation costs and loss of life and property.

Improving Hurricane Intensity Forecasts



Improvement in hurricane intensity forecasts using the Statistical Hurricane Intensity Prediction Scheme, which incorporates Oceanic Heat Content derived from satellite altimetry, for six major hurricanes that occurred during the 2003, 2004 and 2005 Atlantic Hurricane Seasons (Isabel, Ivan, Emily, Katrina, Wilma and Rita). The actual improvement in terms of knots (kt; nautical miles per hour, 1 kt=0.514 m/s) is shown above each bar, and the number of cases (in parentheses) is listed below the forecast hour.

February 2010 blizzards

Two major snowstorms hit the mid-Atlantic region of the U.S. in early February 2010. The combined snow accumulation from these storms – over 50 inches in many regions – placed the 2009-2010 snow season well above the historical record in the Baltimore and Washington DC area. The blizzards caused significant social and economic disruptions in the region – power was cut to hundreds of thousands of people, many roads went unplowed for more than a week, the federal government was closed for four days, and numerous school districts were shut down for nearly two weeks.

A skier in front of the U.S. Capitol on Feb 6, 2010. (Photo credit: Getty Images)

Snowfall

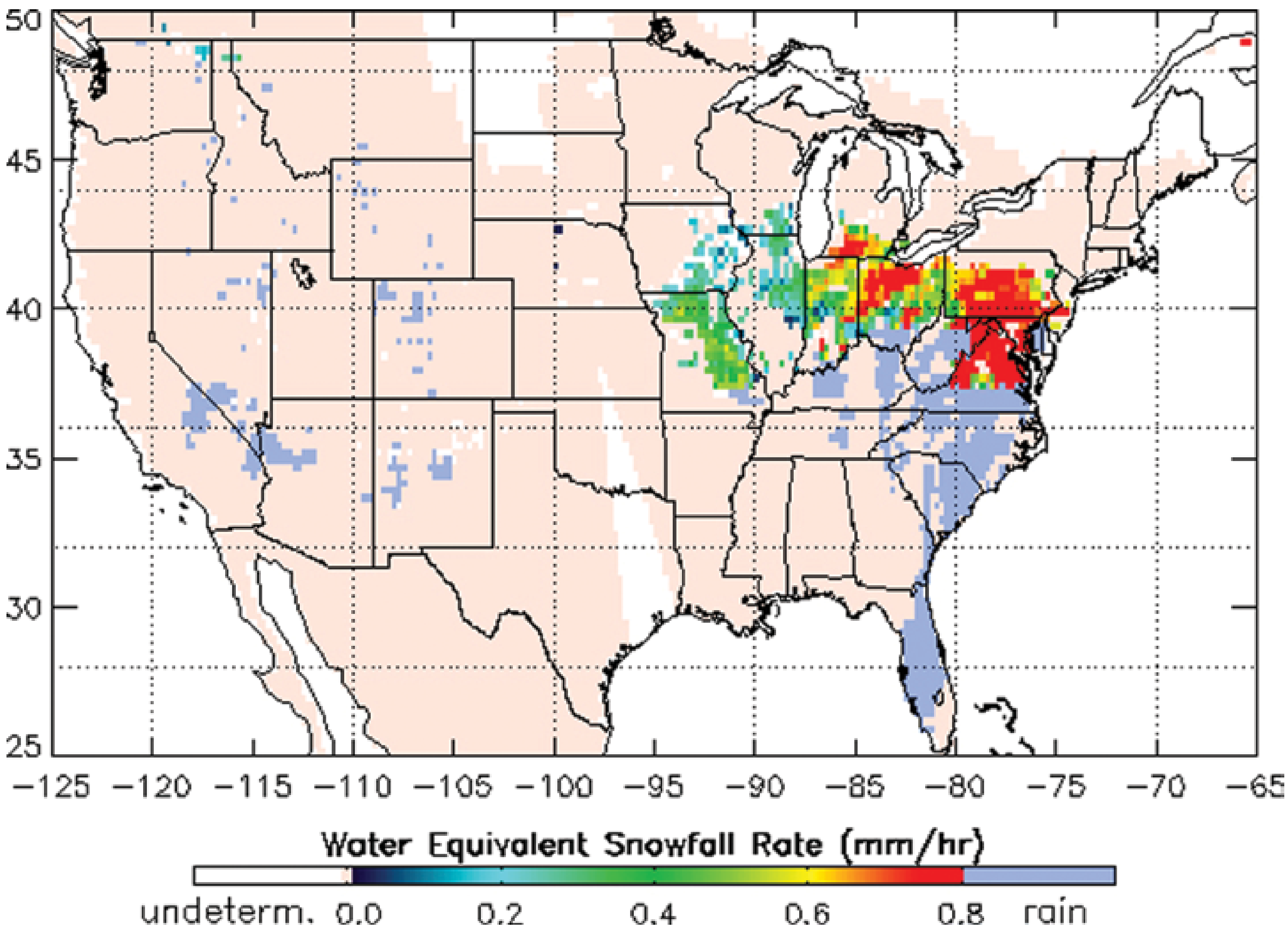
Huan Meng and Nai-Yu Wang

Snowfall is a major form of precipitation in mid-to high-latitude regions. It accounts for about 8 to 10 percent of total world-wide precipitation, and plays an important role in the global water cycle. Freshwater from snowmelt provides the main source of water for human, animal, and plant sustenance in many areas of the world. However, snowfall can also pose a threat to the normal functioning of societies. Even moderate snowstorms often cause problems ranging from serious economic disruptions to significant injuries and deaths. For these reasons, effective monitoring of snowfall has many intrinsic societal benefits well beyond water resources management and weather forecasting interests.

Ground-based snowfall observations are usually inadequate, and very often non-existent, due to a variety of challenges. Observations from polar-orbiting satellites provide an effective way to monitor snowfall with global coverage. Microwave (MW) frequency measurements from satellites are used to detect snowfall and retrieve snowfall rates. Unlike infrared and visible sensors, which can only observe the top of clouds, MW signals can penetrate clouds and detect the environmental conditions within and below the clouds. This advantage gives MW sensors the ability to receive signals that contain the "signature" of snowfall.

Snowflakes are single ice crystals or their aggregates that can scatter electromagnetic signals. Some MW frequencies respond strongly to such scattering, and are significantly depressed in the presence of snowfall. By utilizing these properties, STAR investigators have constructed snowfall retrieval algorithms that use MW measurements from a combination of frequencies.

Snowfall Rate



A map of snowfall rate (water equivalent) retrieved using satellite measurements during the February 5-6, 2010 blizzard in the mid-Atlantic region. This storm produced record breaking snowfall in many areas across the region.

Satellite data assimilation, golf, and the pre-satellite era

How is satellite data assimilation related to weather forecasting?

Satellite data, in combination with conventional observations and a short term Numerical Weather Prediction (NWP) forecast, provide a global snapshot of the Earth's environment (atmosphere, land, oceans, cryosphere) several times a day. This snapshot, called an analysis, serves as the input to sophisticated weather forecasting models. For a reliable weather forecast, it is critical to have initial conditions that are as accurate as possible. One can compare the importance of the analysis for weather prediction to the importance of precisely striking a golf ball to reach a hole. And just as in golf, where the player usually strikes the ball several times before reaching the hole, satellite data assimilation is also performed several times a day by meteorological centers, each time readjusting more or less the state of the analysis to obtain a better forecast.

Prior to meteorological satellite data?

In the past, data assimilation relied exclusively on conventional data (balloon-borne radiosondes, ground measurements, etc) to measure the pulse of our planet. These measurements were sparse and concentrated in specific areas. Although conventional observations are still a source of data for assimilation, measurements from Earth-Observing satellites have become the cornerstone of weather-oriented data assimilation. They offer global coverage, multiple times a day, and provide unprecedented insight into the state of the planet through their measurements of atmospheric clouds, ice, rain, temperature, moisture, and winds, and surface characteristics of snow, sea-ice, vegetation, etc.

Satellite Data Assimilation

Sid-Ahmed Boukabara

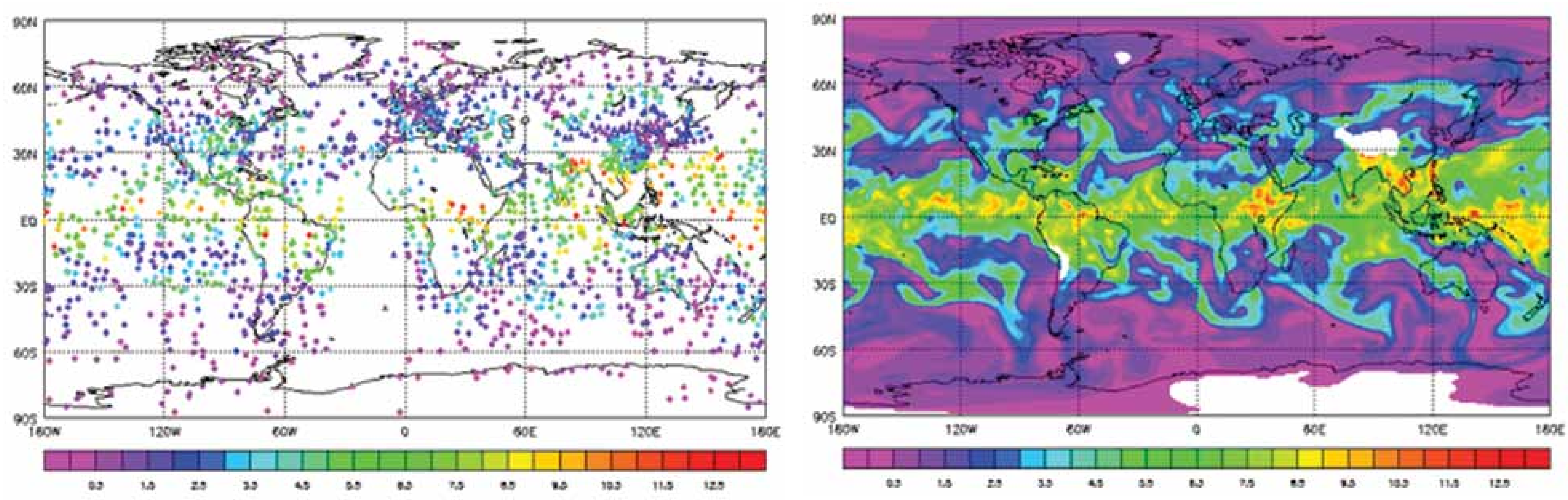
Data assimilation is a scientific technique for merging satellite and conventional observations with the short term (~6 hr) forecast of a numerical weather prediction (NWP) model to provide a "best estimate" of the atmospheric state. It requires knowledge of fundamental physics, radiative transfer, remote sensing, mathematics, several environmental sciences, and meteorology. Data assimilation helps to increase weather forecast accuracy at global and regional scales. This is achieved by offering global and frequent coverage of the Earth's environment at high enough spatial and temporal resolutions. These frequent snapshots of the Earth's status, called analyses (see figure), serve as initial conditions for sophisticated NWP models. Satellite observations provide over 95% of the observations used to generate these initial conditions.

Modern satellite data assimilation relies on a combination of several geostationary and polar-orbiting satellites to allow optimal coverage. Satellite data are assimilated in global models, with physics focused on synoptic scale (~1000 km) weather systems (for example, mid-latitude cyclones), and in regional models, where mesoscale (~10 to 100 km) weather events (for example, thunderstorm systems) are modeled. Satellite data assimilation is therefore crucial for the prediction of medium-range (out to a week or more) weather at global scales, as well as for the prediction of severe storms, hurricanes and typhoons at regional scales.

Satellite data usually have a greater positive impact on weather prediction accuracy in the Southern Hemisphere than in the Northern Hemisphere. The main reason for this is the prevalence of conventional data in the Northern Hemisphere. Other applications of satellite data assimilation include climate variability assessment (through reanalyses data sets), model development, and support of strategic decisions in observing system development.

A number of STAR scientists contribute to the management and research of the NASA-NOAA-DoD Joint Center for Satellite Data Assimilation.

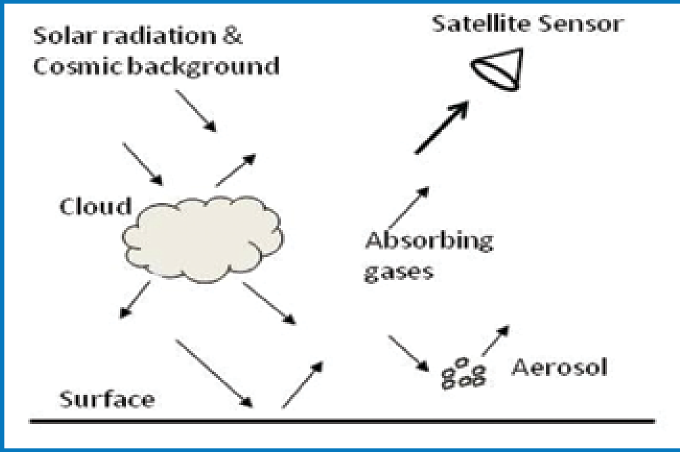
Generating a Global Humidity Field from Sparse and Irregular Observations



Humidity observations (in units of water vapor mixing ratio, g/kg) (left panel) from radiosondes are sparser than the model grid, and highly irregular in their spatial and temporal distribution. Both qualitatively and quantitatively, it is difficult to reconstruct the full humidity field from these data alone. In contrast to the observational dataset, the humidity analysis (right panel) resulting from the data assimilation system (including satellite data) is global. This analysis reveals the signature of dynamical and physical processes at a level of detail that cannot be extracted directly from the observations themselves. (Maps courtesy of Lars-Peter Riishojgaard).

Radiative transfer theory

Radiative transfer is the physical phenomenon of energy transfer in the form of electromagnetic radiation. Radiation is characterized by its intensity, wavelength, and polarization. The propagation of radiation in the atmosphere-surface system is affected by absorption, emission and scattering processes. Radiative transfer theory provides the physical foundation for understanding these processes. The equation of radiative transfer describes the radiative transfer theory mathematically. Equations of radiative transfer have application in a wide variety of subjects including optics, astrophysics, atmospheric science, and remote sensing. A radiative transfer model is a piece of computer software that solves the radiative transfer equation numerically. In remote sensing and NWP data assimilation, such models are used to simulate the amount of radiation received by an Earth-viewing radiometer.



Community Radiative Transfer Model

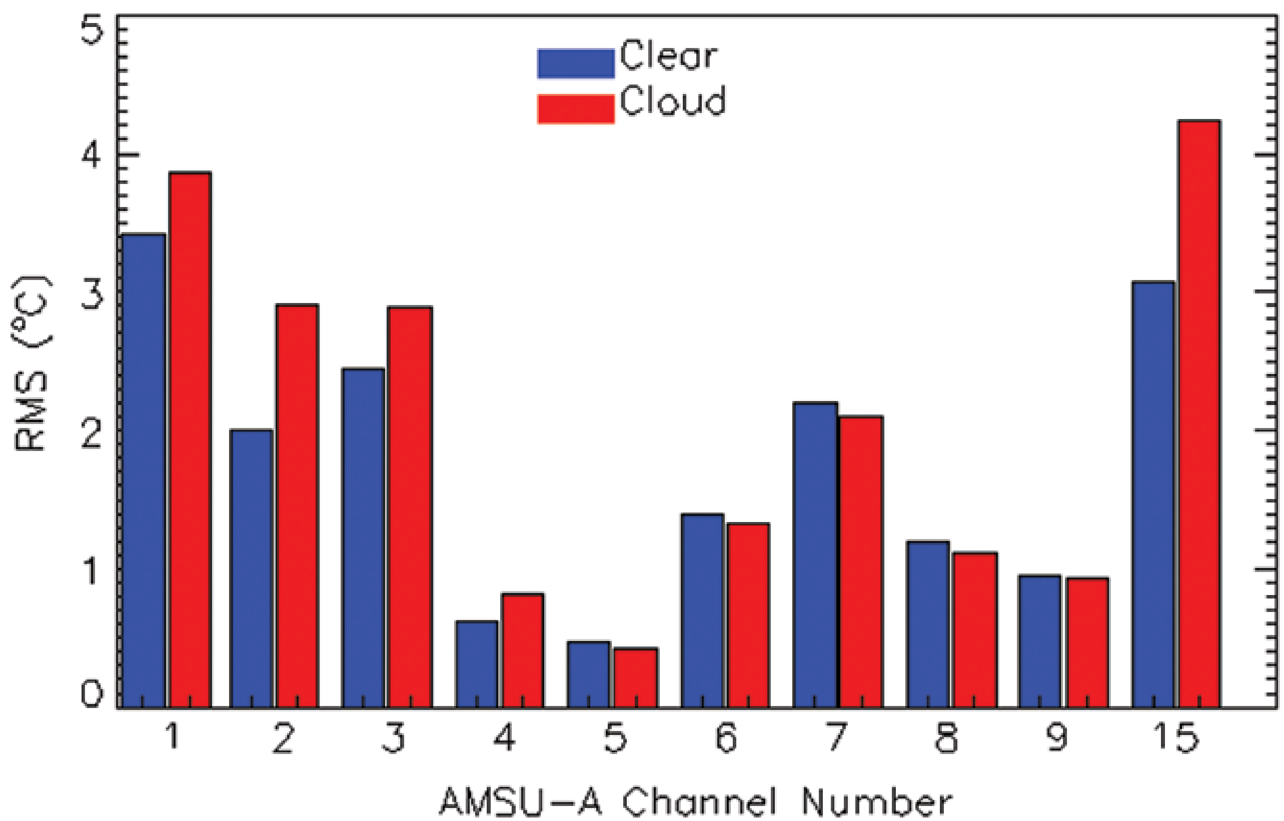
Yong Han, Fuzhong Weng, Paul vanDelst, Quanhua Liu, Yong Chen, David Groff and Banghua Yan

Since remote satellite observations of the radiation reflected and emitted by the Earth are affected by atmospheric and surface conditions – surface and atmospheric temperatures, atmospheric composition, clouds, rain, and snow, and surface reflectivity – it is possible to retrieve quantitative information about the Earth if one can relate the observations to these characteristics. A radiative transfer model provides the glue that ties the satellite observations to the Earth's properties.

For use in numerical weather prediction (NWP) models, the radiative transfer model has to be both fast – after all, the forecast has to be produced before the weather arrives – and accurate. The Community Radiative Transfer Model (CRTM), conceived and developed in large part by STAR scientists for the NASA-NOAA-DOD Joint Center for Satellite Data Assimilation, has been adopted by a number of NWP centers in the U.S. and abroad. The CRTM is a vital part of the NWP model and enables assimilation of the satellite observations to provide initial conditions for the forecasts. It is capable of calculating radiation streams through the atmosphere that are affected by gases, aerosols, clouds, and precipitation particles at wavelengths ranging from the ultraviolet to the microwave. The CRTM supports more than 100 currently in-orbit and historical radiometric instruments.

One current research focus is on improving the calculations for cloudy atmospheres. The illustration on the opposite page shows that the accuracy of cloudy sky calculations is approaching that of clear sky simulations.

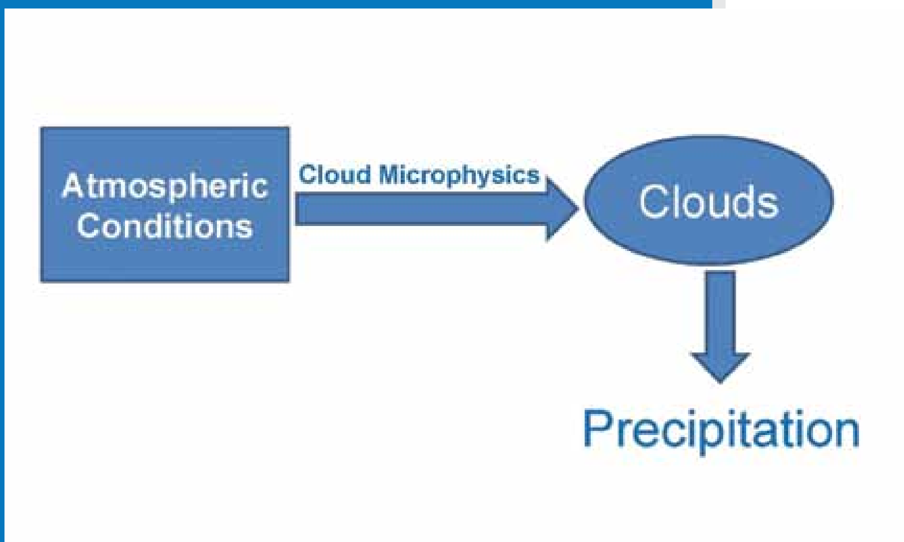
The Community Radiative Transfer Model: Cloudy Atmospheres



Root-Mean-Square (RMS) differences (degrees C) between observed and simulated brightness temperatures – a measure of the radiant energy – of the Advanced Microwave Sounding Unit-A for cloud-free (blue) and cloudy (red) cases for 10 different instrument channels (wavelengths). Calculation of radiative transfer through clouds is a complex problem, but the graph shows that the CRTM calculations for cloudy skies are almost as good as those for clear conditions.

A cloud-resolving model and associated precipitation

Favorable atmospheric temperature and water vapor conditions lead to the development of clouds through cloud microphysical processes. These processes include condensation of water vapor into cloud drops or ice particles and growth of these hydrometeors through collision, accretion, riming, and other processes. When the hydrometeors are large enough, they fall to the ground as precipitation – either rain or snow depending on the atmospheric temperatures. Cloud-resolving models with fine spatial resolutions (~1 km) can simulate the rain events resulting from the microphysical processes in weather producing clouds.



Cloud Resolving Models

Xiaofan Li

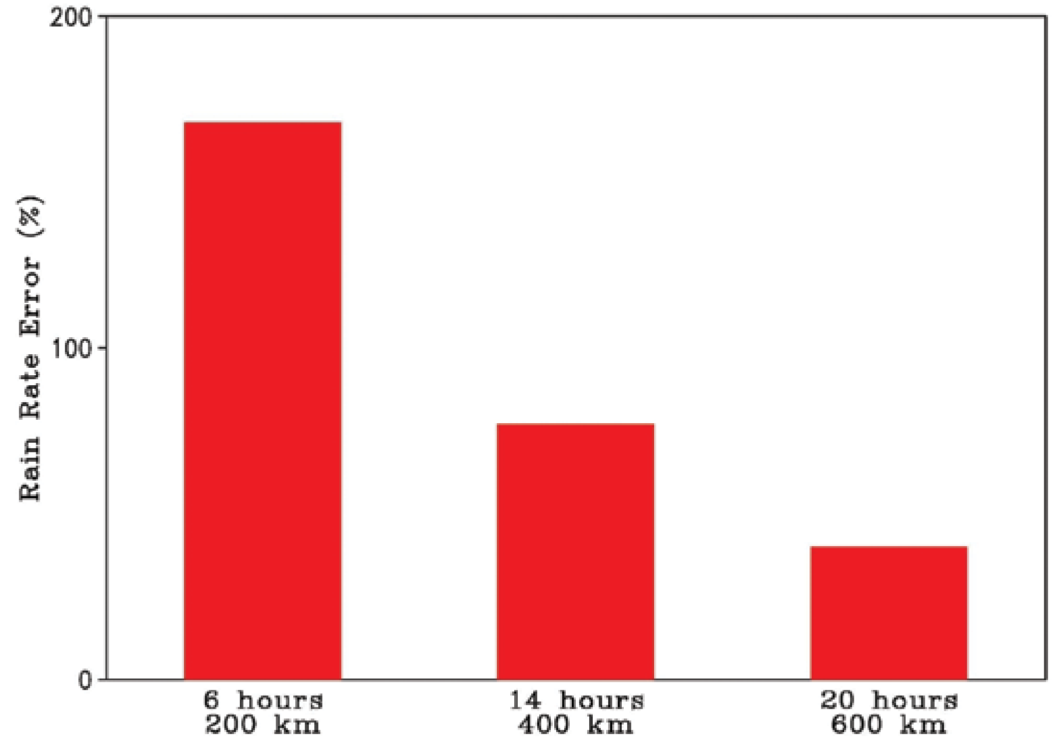
The range of skillful numerical weather prediction (NWP) forecasts has increased at the rate of about one day per decade over the past few decades. For example, today's 4-day forecasts are about as accurate as 3-day forecasts were just 10 years ago. These accomplishments have been achieved without information on what we normally think of as weather – cloudiness and precipitation – in the initial conditions of the NWP models.

A number of obstacles currently lie in the way of assimilating such observations, and state of the art NWP models are today initialized primarily with observations of clear skies. One of the obstacles is our inability to construct computer models of the complex processes involved in cloud and precipitation formation, a necessary first step to assimilate cloud/precipitation observations.

The horizontal and vertical resolutions of NWP models are too coarse – 10 to 100 km in the horizontal – to model the micro-physical processes involved in the formation of individual clouds. These processes can only be parameterized (approximated). One approach to improving the numerical modeling of clouds in NWP models is to exploit the results of cloud resolving model research. Cloud resolving models have resolutions small enough – 1 km in the horizontal – to capture the essential physical processes, and the results of tests of these models can be used to obtain better approximations for the NWP models.

STAR scientists are evaluating cloud resolving models as one step in improving NWP cloud parameterizations with the ultimate goal of facilitating assimilation of satellite cloud and precipitation observations in NWP models.

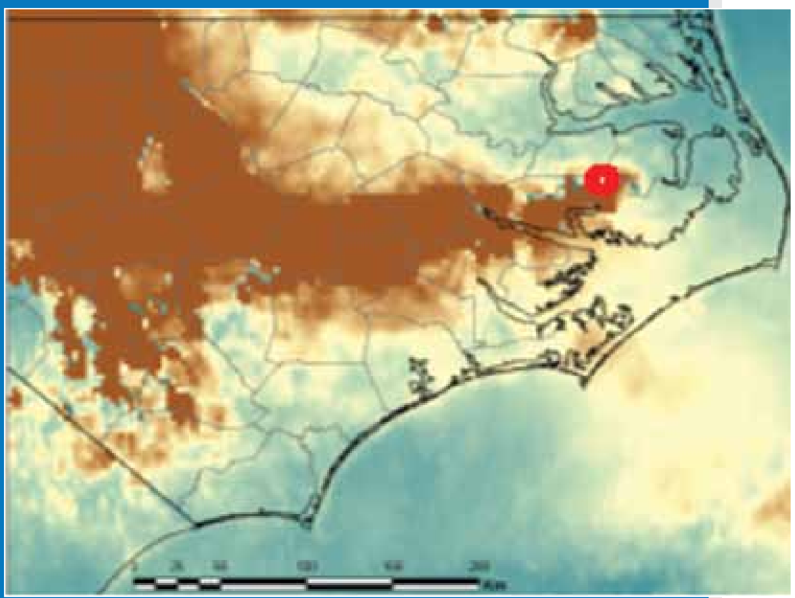
Evaluation of Precipitation from a Cloud Resolving Model



Time and spatial-scale dependence of rain-rate error (%) in a tropical rainfall case simulated using a two-dimensional cloud-resolving model. Rain-rate error decreases as the time period and area for which the error is computed increase. Results from cloud resolving models can be used to improve numerical weather prediction modeling of clouds with an ultimate goal of assimilating satellite cloud and precipitation observations.

Emergency room visits for heart failure

During an intense smoke pollution event during the summer of 2008, hospitals in North Carolina experienced a 37% increase in emergency room visits for heart failure. Patients with prior poor health were most susceptible to the high smoke levels. Satellite monitoring provided scientists from the Environmental Protection Agency (EPA) with data to study the link between pollutant levels and resulting emergency room visits.



The color-coded map shows Daily Mean Aerosol Optical Depth (AOD) observed by GOES-12 on June 11, 2008 over rural North Carolina. The AOD range is from 0.0 (green) to 2.0 (brown). The high values are due to smoke from a fire whose location is shown by the red dot. The EPA used NOAA's GOES AOD measurements as a proxy for pollution exposure during the wildfire.

Air Quality

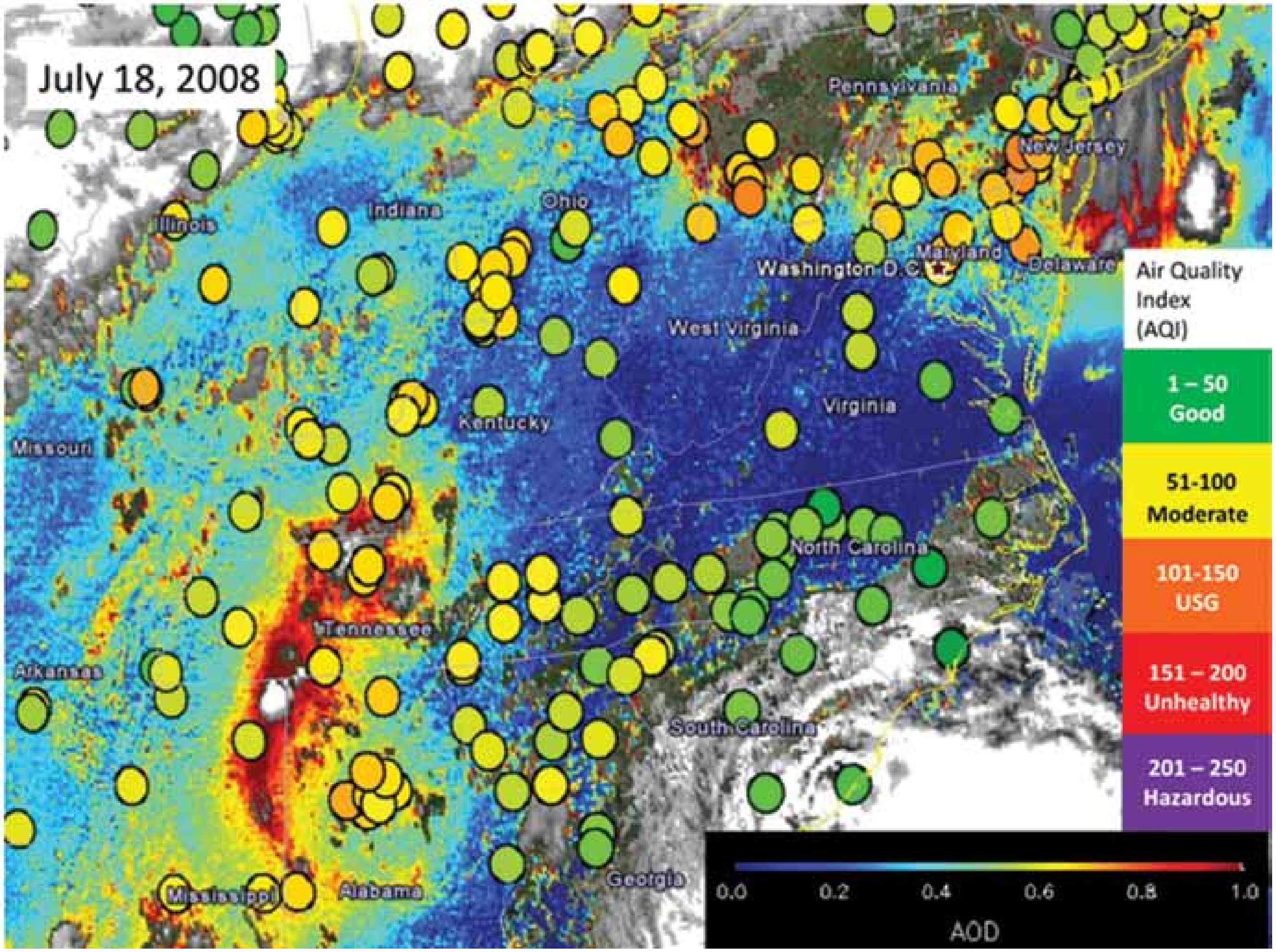
Shobha Kondragunta

Aerosols (airborne dust-like particles) are a key component of urban/industrial photochemical smog. They are also the primary pollutant in natural environmental disasters such as volcanic eruptions, dust outbreaks, biomass burning associated with the clearing of forests for agricultural purposes, and forest fires. High concentrations of aerosols, when inhaled, lead to upper respiratory diseases including asthma. They decrease visibility and lead to unsafe conditions for transportation. The Environmental Protection Agency (EPA) estimates that more than 106 million people in the United States live in areas of poor air quality, costing about $143 billion dollars per year in hospital expenditures.

The Aerosol Optical Depth (AOD) is a measure of the amount of aerosol in a vertical column from the Earth's surface to the top of the atmosphere. By measuring AOD from satellites, one can obtain information on surface aerosol concentrations for air quality monitoring and forecasting applications. Visible imagery from NOAA's GOES satellites is used to derive pollution information for the United States.

STAR scientists are working to integrate the satellite measurements into air quality prediction models. The combination of numerical weather prediction guidance and satellite aerosol imagery in real time will improve air quality warnings and alerts. Analyses of the satellite data aid the EPA in its development of pollution mitigation strategies.

Do Satellite Air Quality Measurements Agree with Surface Monitors?



Aerosol Optical Depth (a measure of amount of aerosol in a vertical column of atmosphere) for July 18, 2008 from NOAA's geostationary satellite is displayed as a color map. Circles with filled colors show Air Quality Index (AQI) as observed by the Environmental Protection Agency's (EPA) ground monitors. The satellite measurements (red/yellow indicates high pollution and blue/green indicates low pollution) are in general agreement with the ground monitors (USG in the AQI scale denotes: Unhealthy for Sensitive Groups).

Nitrogen Dioxide

Trevor Beck

Nitrogen dioxide (NO_2) is a direct precursor of ground level ozone, an air pollutant that causes harmful health effects in people, plants, animals, and livestock. NO_2 is also a damaging pollutant in its own right, leading to decreases in atmospheric visibility. It was a major contributor to the Brown Cloud episodes in Denver in the 1980's. The primary sources of NO_2 are smokestack emissions and automobile traffic (with conventional combustion engines). NO_2 is short lived, on the order of hours. It peaks in the morning in polluted regions and gradually decreases until sunset. NO_2 is converted to ground level ozone by strong sunlight in a photochemical process.

Ground level ozone is difficult to measure from space, but by measuring the tropospheric NO_2, the approximate amount of surface ozone may be inferred. Thus, the NO_2 measurements serve as a proxy for ground level ozone and for poor air quality.

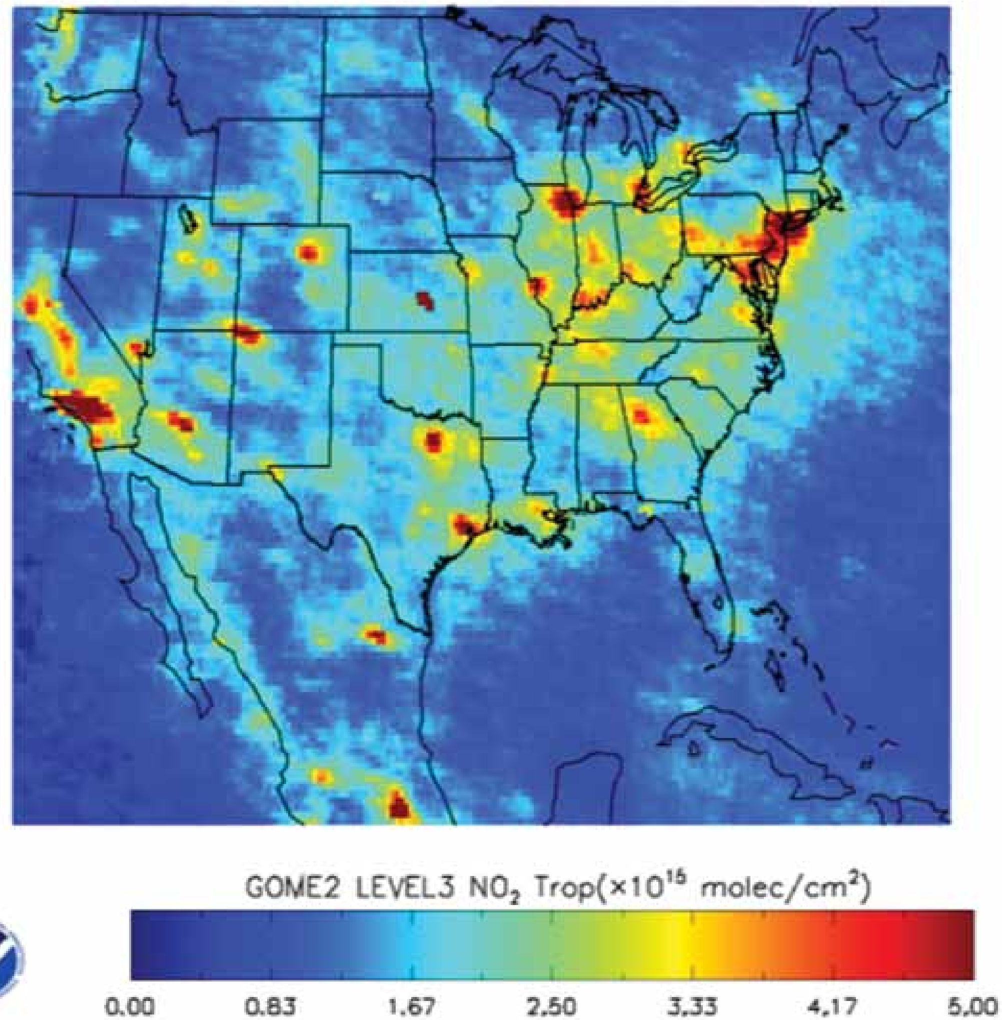
STAR has developed the methodology to measure the amount of tropospheric NO_2 from observations of the Global Ozone Monitoring Experiment–2 (GOME-2) instrument on the METOP-A polar orbiter. This methodology has recently been implemented operationally at NOAA, and near-real time daily global measurements are produced. Merging the satellite NO_2 data with in-situ measurements in air quality models should lead to more accurate pollution forecasts.

Why is brown smog brown?

During the 1980s the city of Denver suffered through a number of severe photochemical smog episodes. Because of the color of the smog, they were called brown cloud, haze, or smog events. The images below show the difference between a clear (top) and smoggy (bottom, with brown smog in the distance) day in Denver. These events caused numerous deleterious effects on the environment, the economy, and human health and well being. The brown color of the smog is in large part due to the high levels of NO_2. NO_2 absorbs the blue rays of the solar spectrum, which together with the preferential scattering of red light by the smog particles, causes the brownish color.

(Photo credit: Copyright University Corporation for Atmospheric Research (bottom)).

Tropospheric Nitrogen Dioxide, Summer 2010



Due largely to emissions from automobiles, NO_2 is greatest in the vicinity of large cities. Note the high concentrations in the Washington, DC-Boston megalopolis and Los Angeles area.

Microburst maritime disasters

Since 2000, microbursts have caused a number of marine transportation disasters resulting in fatalities or the total loss of a vessel.

In February 2010, the Canadian Sailing Vessel (SV) Concordia (below) capsized and sank in a microburst that occurred 290 nautical miles south-southeast of Rio de Janeiro. Amazingly, all 64 of the passengers on board, including crew, faculty, and students, survived the overturning and sinking of the ship.

In March 2004, the “Lady D”, a water taxi servicing the Baltimore Harbor, was flipped over by a strong microburst, causing five fatalities and injuring many more.

These events underscore the importance of detecting the hazardous winds produced by isolated and intense thunderstorms and warning vulnerable vessels.

(Photo credit: West Island College Class Afloat, Lunenburg, Nova Scotia, Canada, B0J 2C0)

Microburst Prediction

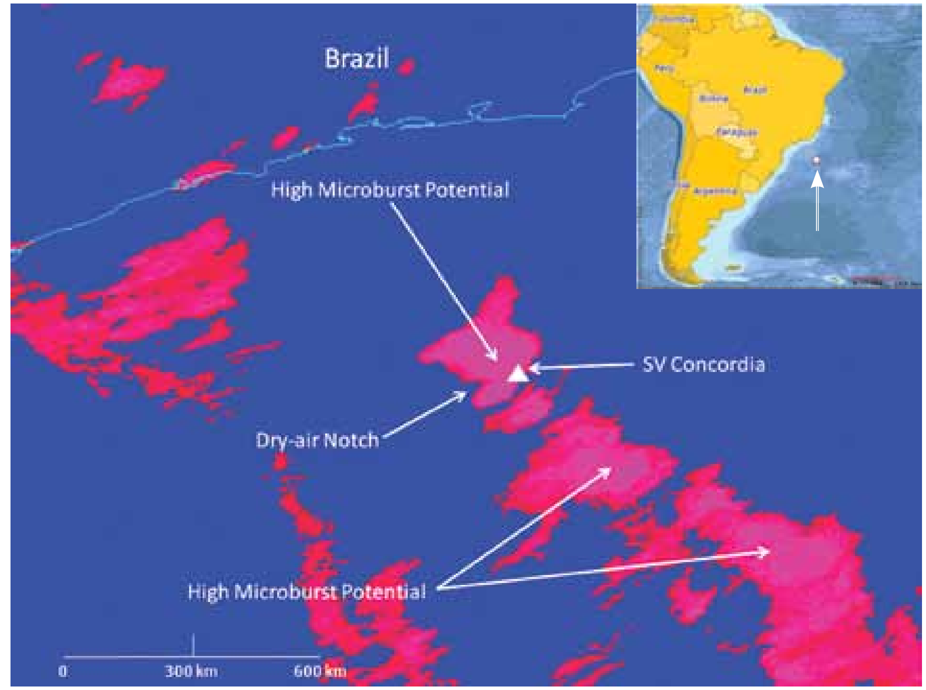
Ken Pryor

A microburst is a strong downdraft that induces an outburst of damaging winds on or near the ground. The intense downdraft is driven by a combination of the weight of precipitation in a thunderstorm and the cooling that occurs due to the evaporation of rain when dry air is ingested into the core of the storm. The environment that is most favorable for the generation of a microburst is a dry air layer in the middle troposphere that overlies a warm and moist lower troposphere. This environment would cause the downdraft to accelerate as it approaches the ground and produce very strong winds upon impact, sometimes in excess of hurricane-force. Microbursts are typically very small with diameters 4 km or less and have lifetimes less than 5 minutes. The small size of the microburst is a major factor in generating the low-level wind shear that is a hazard to aviation and marine transportation.

STAR researchers have found that particular signatures or patterns in GOES imagery are useful in the short-term prediction of microburst potential. These features are associated with the generation of intense thunderstorm downdrafts. A “dry-air notch” in GOES infrared imagery is a V- or U-shaped region of relatively warm brightness temperature that typically appears on the rear flank of a microburst-producing thunderstorm. The dry-air notch can signify the development of a microburst as dry air is being channeled into the thunderstorm core. The dry-air notch has been associated with numerous significant microburst events over the past decade.

National Weather Service forecast offices integrate the satellite measurements with other data to predict these events and issue timely and effective warnings.

Sinking of the Concordia



Conceptual model of a microburst-producing convective storm (left) and GOES-12 imager microburst product at 1709 UTC 17 February 2010 (right) that indicates a microburst in progress over the South Atlantic Ocean off the coast of Brazil. The white triangle marks the location of the sinking of the Sailing Vessel (SV) Concordia by a microburst at 1722 UTC. Magenta shading indicates very cold cloud tops associated with intense thunderstorms. Note that the dry-air notch was pointing toward the location of the Concordia, and, thus, the vessel was in the direct path of downburst winds. Also, it appears that the Concordia was in an optimal location to experience both the horizontal and vertical components of the downburst winds. (Photo credit: NASA (left); Planiglobe (right))

High impact eruptions in 2009 and 2010

The economic impacts of airborne volcanic ash are significant. For instance, Alaska Airlines was forced to cancel 295 flights (stranding over 20,000 passengers) in March and April of 2009 due to ash clouds produced by Mount Redoubt. While the economic impact of the 2009 Redoubt eruptions is still being tabulated, the total estimated cost of eruptions of Redoubt in 1989-1990 was $160 million. In April and May 2010, volcanic ash from the eruption of Eyjafjallajökull in Iceland shut down commercial aviation in Europe for several days. The total economic impact of the Eyjafjallajökull eruption was over 2 billion dollars.

Over 100,000 flights were cancelled during the eruption of Eyjafjallajökull in April and May 2010 (Photo credit: Getty Images).

Aviation Hazards: Volcanic Ash

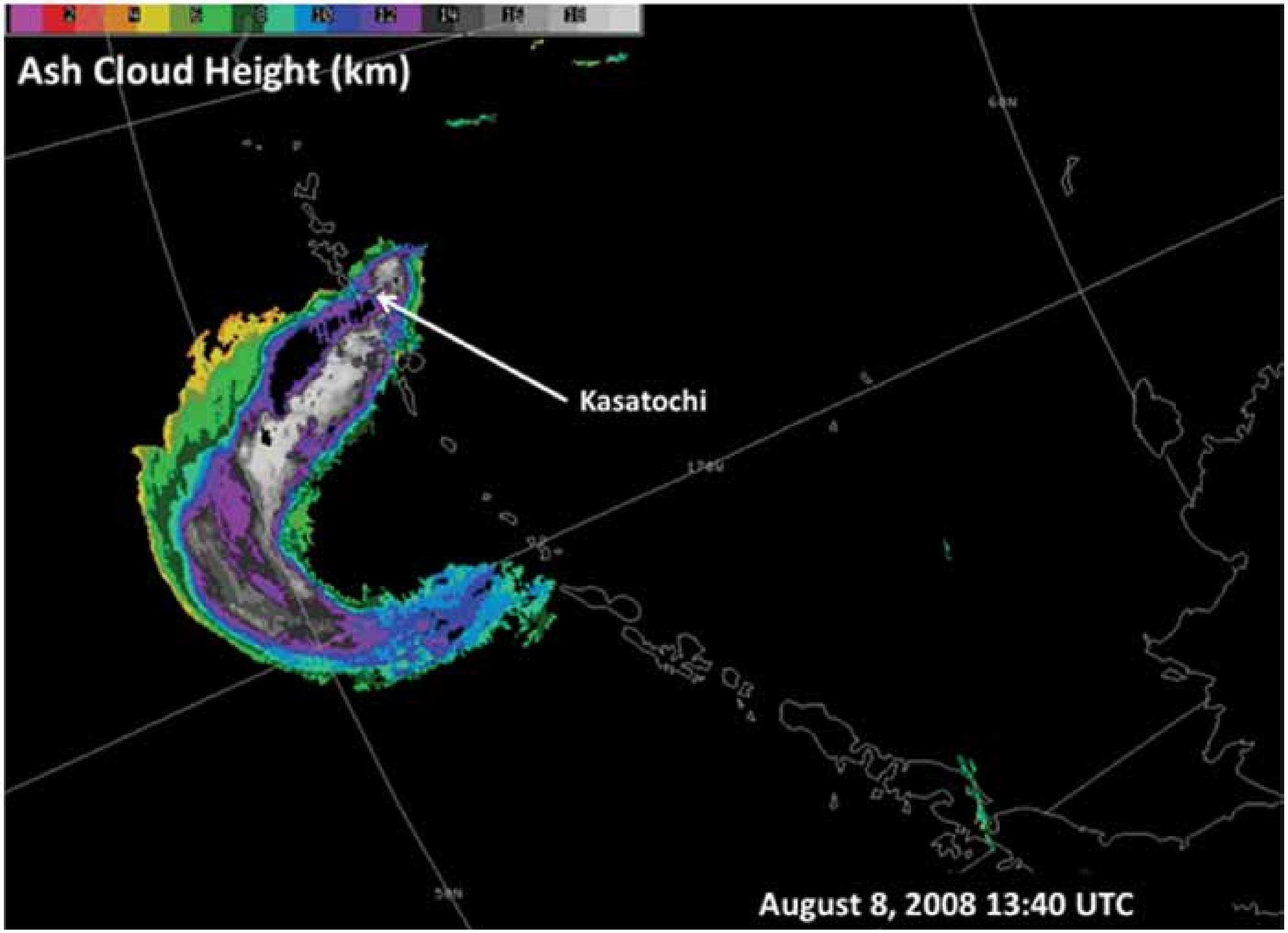
Michael Pavolonis

Airborne volcanic ash is a major aviation, health, and infrastructure hazard. When ingested into aircraft engines, volcanic ash causes engine damage or failure. For example, in December 1989, a 747 jetliner carrying 231 passengers encountered an ash cloud during an eruption of the Mount Redoubt volcano, located southwest of Anchorage, AK. Within 60 seconds of encountering the heavy ash cloud, all four engines of the aircraft had stalled. Fortunately, the pilot was able to restart the engines, narrowly avoiding a crash. Volcanic ash is extremely abrasive, and even small concentrations can cause severe damage to the exterior of aircraft. In addition, ash falls pose significant health and infrastructure threats to those on the ground.

Satellite-based measurements of infrared radiation have been the primary means for tracking volcanic ash clouds since the 1980's. While measurements at ultra-violet, visible, near infrared, and microwave wavelengths are also useful for monitoring volcanic ash clouds, infrared measurements are available day and night on many geostationary and polar satellites.

In the infrared part of the spectrum, the amount of radiation absorbed by volcanic ash generally decreases as the wavelength of the radiation increases. The opposite is true for weather clouds. Thus, volcanic ash clouds can often be differentiated from other types of clouds. Infrared measurements can also be used to determine the properties (e.g., height and concentration) of ash clouds. In recent years, STAR scientists have developed greatly improved methods to detect volcanic ash clouds and quantify their properties. These satellite measurements are critical for volcanic ash cloud warnings and forecasts.

Kasatochi Erupts and Sends Volcanic Ash to 20 km



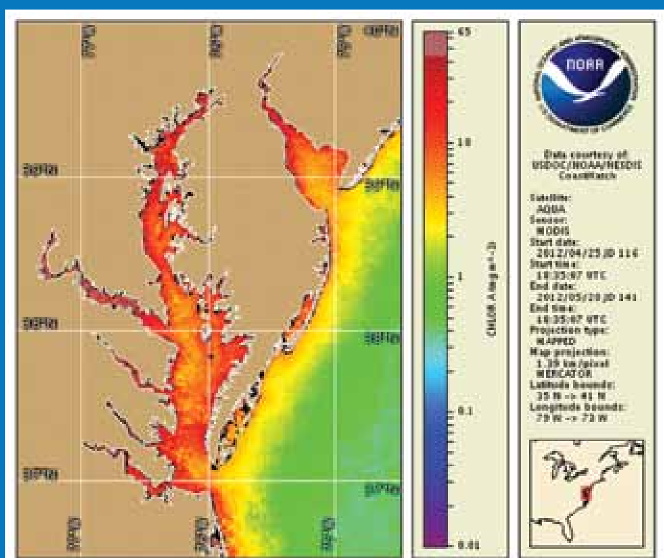
A map of ash cloud top height (km) after the eruption of Kasatochi, Alaska, on August 8, 2008. The ash cloud heights (color bar scale, with grey indicating the greatest heights) are derived from infrared satellite measurements and are critical for locating the ash and forecasting its spread.

Section 4

Oceans

At land's end…

Coastal zones are dynamic, productive regions, occurring at the interface of the atmospheric, oceanic and terrestrial domains (e.g., Chesapeake Bay below). Significant impacts also result from the large human populations that live in close proximity to the oceans. Satellites provide routine global coverage and are crucial for understanding and monitoring oceanic conditions. However, ocean phenomena can be difficult to characterize given their complexity and variability, as well as due to cloud cover which can obscure satellite observations. In particular, small-scale, episodic and/or ephemeral features such as eddies, plumes and blooms, although common in coastal waters, can be difficult to monitor. Future satellite missions will provide increased spatial, temporal and spectral resolution, improving our ability to understand and monitor coastal waters.



MODIS-Aqua image of chlorophyll-a concentrations (a proxy for phytoplankton biomass) in Chesapeake Bay.

Planet Ocean

Paul DiGiacomo and Marilyn Yuen Murphy

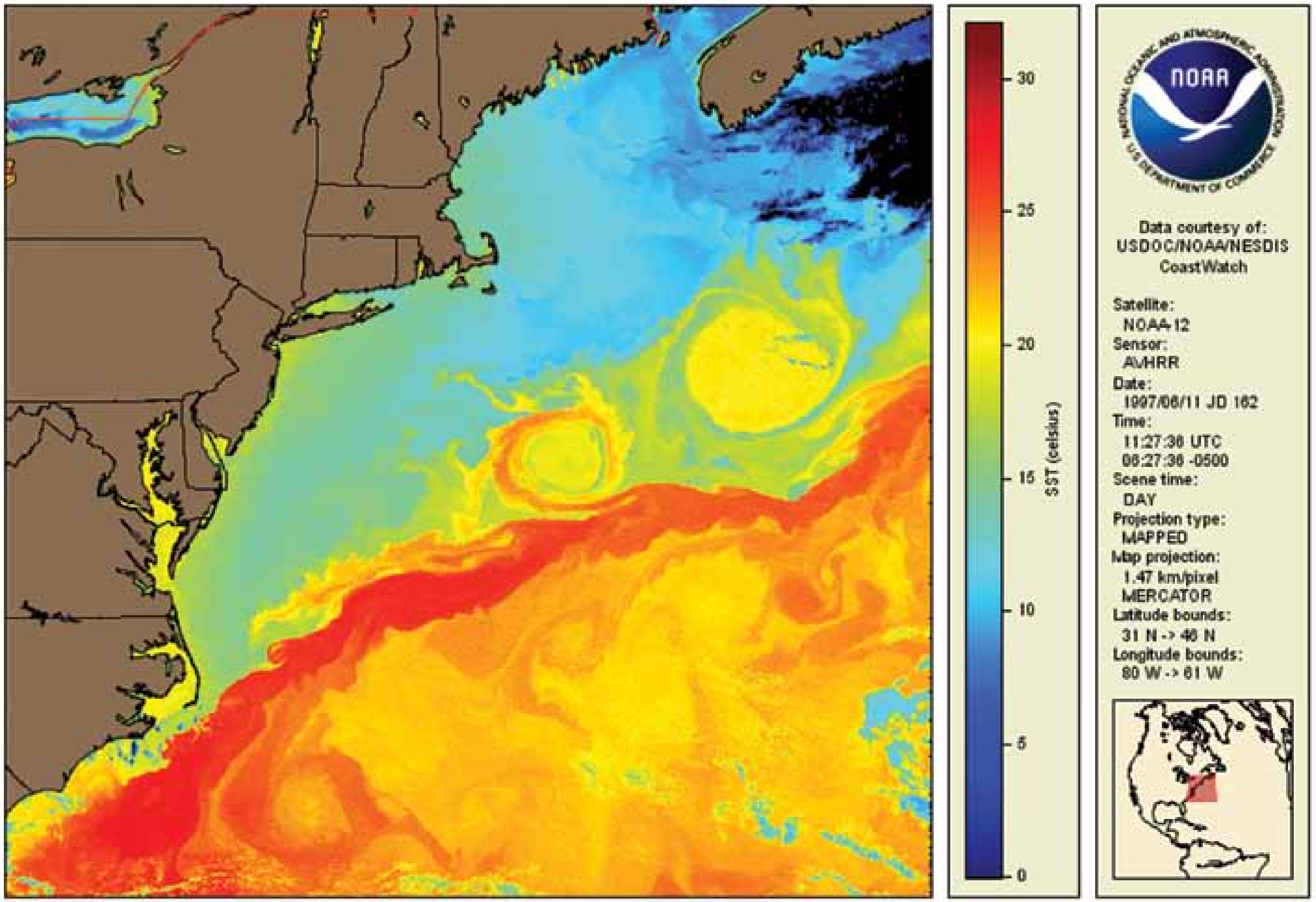
The world's oceans span more than 70% of the surface of our planet and contain approximately 97% of its water. They significantly influence Earth's weather. For example, currents like the Gulf Stream (see figure opposite page) can drive hurricane intensification. The oceans play a critical role relative to climate variability and change; topics such as carbon cycling, ocean warming, acidification and sea level rise are currently of great interest. The oceans are also extremely important from a socio-economic perspective by providing valuable goods and services (e.g., fisheries, energy, transportation, tourism, and recreation).

From a global perspective, the ocean plays a significant role in the carbon cycle (e.g., solubility and biological "pumps"), the water cycle (e.g., evaporation and terrestrial runoff), and the cycling of nutrients (e.g., nitrogen, phosphorus). A majority of the global population lives close to a coast. Ocean impacts on the coastal population can come from sea level rise, storm surges, tsunamis and other inundation events, harmful algal blooms, etc. In turn, anthropogenic impacts on the coastal zone and ocean waters include loss and modification of habitat, pressures on living marine resources, and water quality concerns such as oil spills, discharge of pollutants and pathogens, eutrophication (increase in plant biomass due to excessive nutrient enrichment) and hypoxia (oxygen depletion).

Observing the ocean can be quite challenging due to its vastness, depth, remoteness from land, and complex dynamics. Observations from satellites are invaluable in advancing our scientific understanding of the ocean and improving our ability to efficiently monitor and manage the ocean and coastal marine ecosystems.

STAR scientists develop and utilize satellite data and products for a number of key ocean parameters. They compare and integrate these data with in situ measurements (for example, from buoys), and support development of modeling approaches and applications to help assess, monitor and manage areas under environmental stress (e.g., coastal zones, coral reefs, and Polar Regions).

The Gulf Stream



Gulf Stream sea surface temperature (SST) derived from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-12. Currents like the Gulf Stream can be recognized in satellite SST imagery by their sharp temperature gradient between warm and cold water. In this image, red/yellow signifies warmer water, and blue/green depicts cooler water. The current flows along the darkest red ribbon in the image, from the southwest to the northeast, manifesting several rings and eddies.

Polar SST: From 1981 to tomorrow

Accurate SST retrievals have been made from the Advanced Very High Resolution Radiometer (AVHRR) flown onboard NOAA satellites since 1981. NOAA AVHRR provides global coverage with 4 km resolution twice daily. The most recent U.S. polar satellite, NOAA-19, was launched in February 2009.

The first European polar-orbiting satellite, Metop-A, was launched in 2006 with an AVHRR capable of measuring global SST with a resolution as fine as 1km. Metop-B and -C will follow and extend the AVHRR record into 2020s.

The Visible/Infrared Imager/Radiometer Suite (VIIRS) is an advanced sensor that builds upon the heritage of the MOderate resolution Imaging Spectroradiometer (MODIS), which was flown on NASA's Terra and Aqua satellites.

With sub-km spatial resolution, more spectral channels, and improved accuracy, it was launched into space in 2011 on the NASA-NOAA Suomi NPP satellite, the precursor to NOAA's next generation Joint Polar Satellite System. As the replacement for the AVHRR, it will provide even more reliable SST observations.

The Visible/Infrared Imager/Radiometer Suite (VIIRS) will measure global sea surface temperatures with unprecedented detail and accuracy. (Photo Credit: Ball Aerospace)

Sea Surface Temperature from Polar Satellites

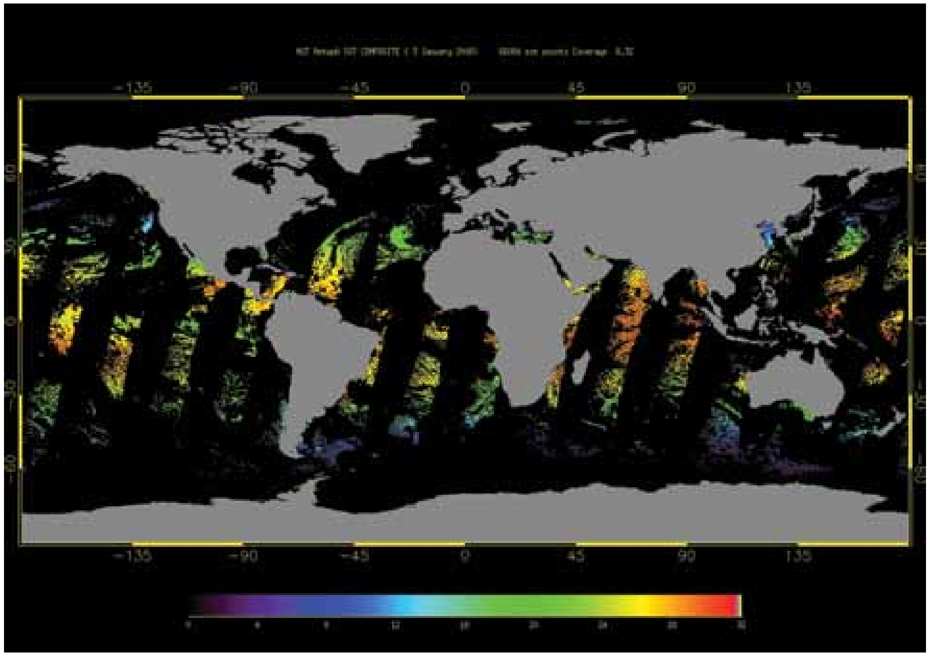
Alexander Ignatov, John Sapper, Xingming Liang, Boris Petrenko, Yury Kihai and John Stroup

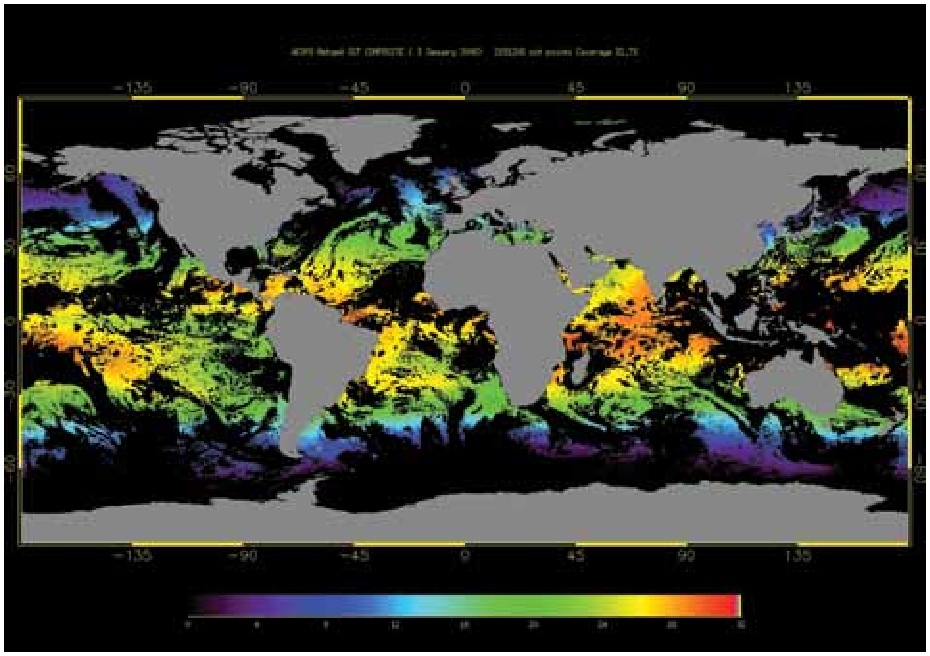
In the early 1980s, NESDIS pioneered the first global operational sea surface temperature (SST) product from satellite observations. The SSTs are derived from IR measurements in "atmospheric windows" – spectral regions that permit the ocean's emitted radiation to pass through the atmosphere with little absorption by atmospheric gases. The instrument – the Advanced Very High Resolution Radiometer – a workhorse of satellite observations and applications, about which an entire book has been written – is still flying on the NOAA and European Metop polar-orbiting satellites. The satellite SSTs have been widely used for research and applications in the fields of climatology, meteorology and oceanography.

Perhaps the most difficult problem in measuring SST is ensuring that one has a clear field of view – i.e., cloud cover, or even small patches of clouds are not blocking the ocean signal. In 2006, STAR initiated a fundamental redesign of the heritage SST processing system, to meet the new more stringent requirements for accurate SST measurements. A key attribute of the new system is a much better way to screen for clouds in the field of view. In May 2008, the new Advanced Clear-Sky Processor for Oceans (ACSPO) product became operational.

The unique feature of ACSPO is the use of the fast Community Radiative Transfer Model, in conjunction with estimates of SST and atmospheric moisture and temperature from numerical weather prediction models, to produce top-of-atmosphere first-guess infrared radiances for clear skies, at each retrieval point. In addition to more accurate cloud screening, the first-guess radiances are also critical for improved SST measurements.

New Versus Heritage Sea Surface Temperature Maps





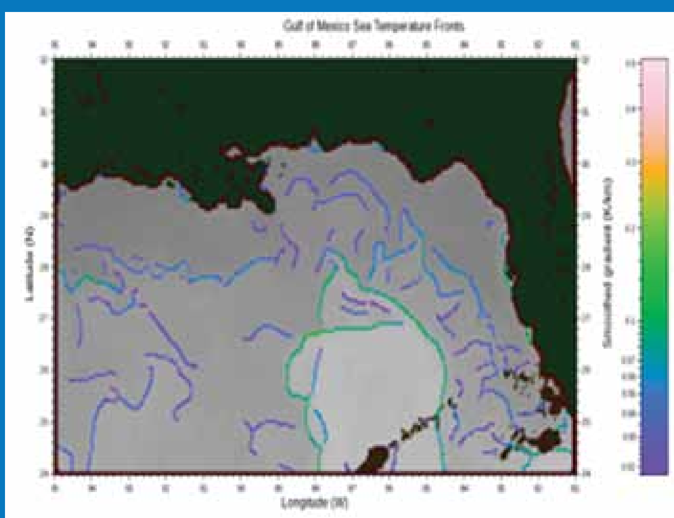
Resolution 8 km
6.6 x 10^4 SST observations
8.3% ocean covered in 1 day

Resolution 4 km
2.1 x 10^6 SST observations
32.7% ocean covered in 1 day

Daytime 24-hour SST composite produced by the heritage NESDIS SST (left) and the new NESDIS (right) systems. Black areas have no measurements because of gaps in observational coverage or cloudiness. The new system provides ~30 times more SST measurements and significantly improves global coverage, with comparable accuracy statistics. In addition to SST, the system also delivers two other products over oceans: clear-sky infrared radiances and aerosols.

Tracking the Gulf of Mexico oil spill with SST observations

Sea surface temperature (SST) fronts (strong horizontal temperature changes represented by wiggly colored lines in the figure) are identified and located in 24 hour composites of SSTs derived from geostationary satellites (GOES-East and GOES-West). Near these fronts, sea water converges, leading to accumulations of oil. As a result, satellites can indirectly help to pin-point the locations of oil plumes – information that can be fed to hazard response officials. The smoothed gradient color bar describes how fast the sea surface temperature is changing per kilometer. For example, the light green in the color bar corresponds to 0.2 degrees Kelvin per kilometer. This translates to a temperature change of 2 degrees across the 10 km wide green frontal zone. The light grey areas are warm regions, the dark grey areas cold regions.



Ocean Temperature: The Continuous View

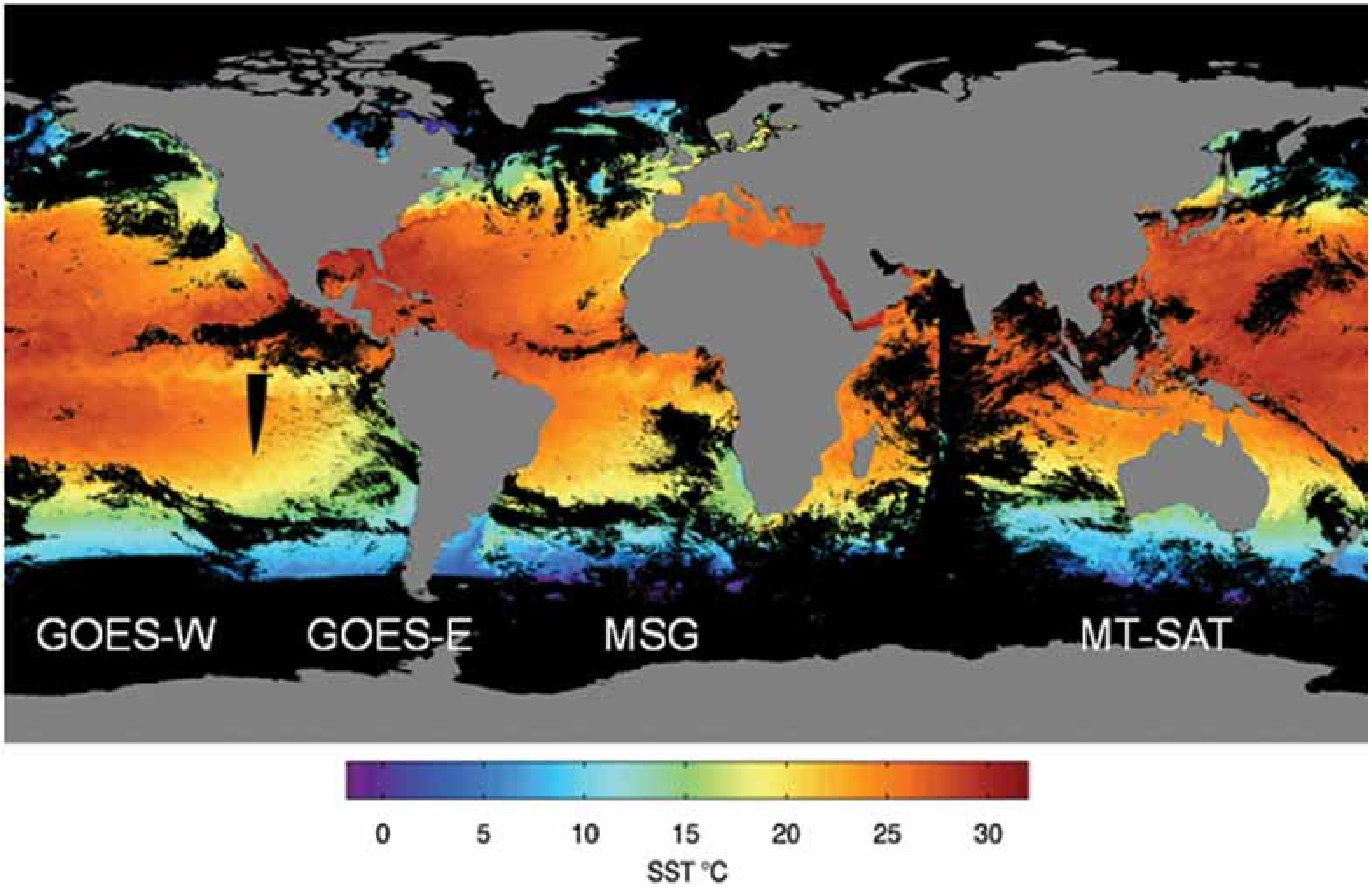
Eileen Maturi and Jonathan Mittaz

Sea surface temperature (SST) derived from infrared (IR) observations by geostationary satellites form a uniquely powerful data set that provides continuous — hourly – updates of global ocean conditions at horizontal resolutions as fine as 4 km. A significant advantage of geostationary satellites over polar satellites is their ability to view the same location almost continuously, substantially increasing the opportunity for the cloud-free views needed to actually see and measure the ocean temperature. Not unexpectedly, such SST data sets have a broad spectrum of applications.

NOAA's National Marine Fisheries Service uses the GOES SST to support commercial fisheries management and protection of endangered species, like monitoring turtle exclusion for fishing and mammal protection. NOAA's Coral Reef Watch Program applies GOES SSTs to its coral bleaching warnings and assessments. NOAA's National Weather Service incorporates GOES SST into its prediction models to improve forecasts of high seas, current and eddy formation, and hurricane tracks. The climate community uses the GOES SST observations to study the phases of the El Niño-Southern Oscillation phenomenon and climate variability.

STAR scientists have developed the algorithms for processing the GOES data and are contributing to the development of algorithms for the next generation of NOAA geostationary satellites – GOES-R.

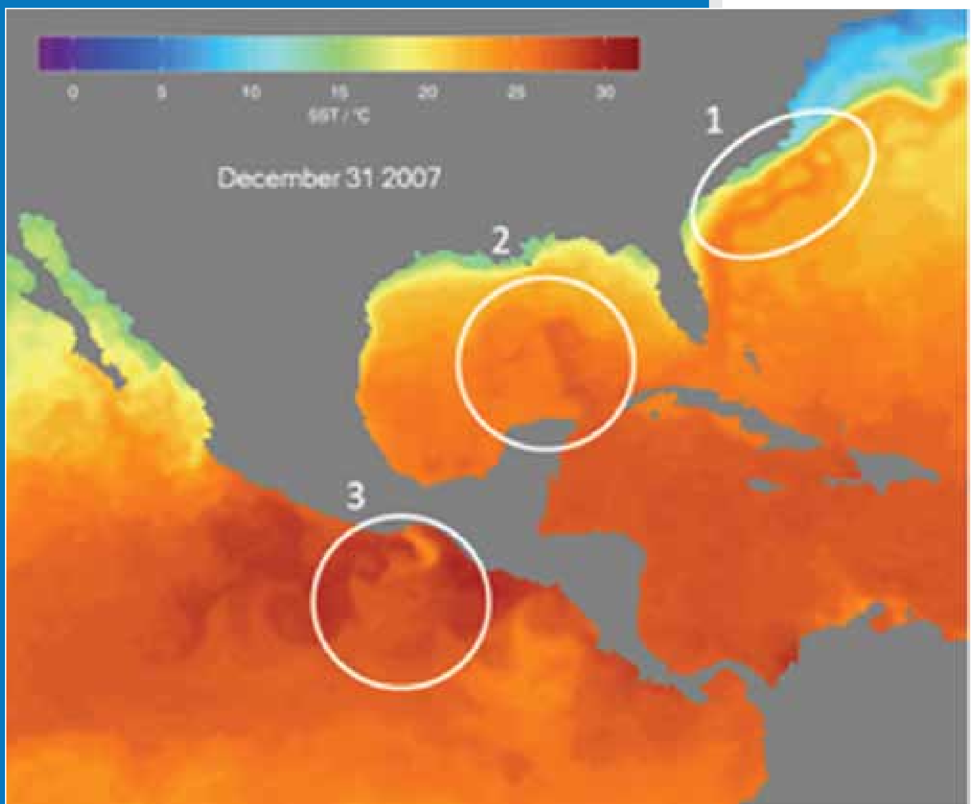
Four Geostationary Satellites: One Global Sea Surface Temperature Map



A 24-hour merged sea surface temperature map derived from geostationary satellites: NOAA's GOES-W and GOES-E, Europe's Meteosat Second Generation (MSG-9), and Japan's Multi-Functional Transport Satellite (MTSAT). Black areas indicate persistent cloudiness during the day, precluding views of the ocean, and creating gaps in the satellite coverage. STAR plans to fill the gap in coverage between MSG and MTSAT in the Indian Ocean with SSTs from the Meteosat Second Generation (MSG-8). The approximate orbital locations over the equator are shown by the satellite names at the bottom of the figure: GOES-WEST (W)-135˚W/GOES EAST (E)-75˚W, MSG -0˚E, and MTSAT -140˚E

Tracking small scale oceanic features

The blended sea surface temperature analysis from geostationary and polar-orbiting satellites allows small scale oceanic features to be continuously monitored and tracked. The image shows the Gulf Stream meanders (1), the loop current and its associated eddies in the Gulf of Mexico (2), and the meanders and eddies in the Gulf of Tehuantepec (3).



GEO-LEO Sea Surface Temperatures

Eileen Maturi and Andy Harris

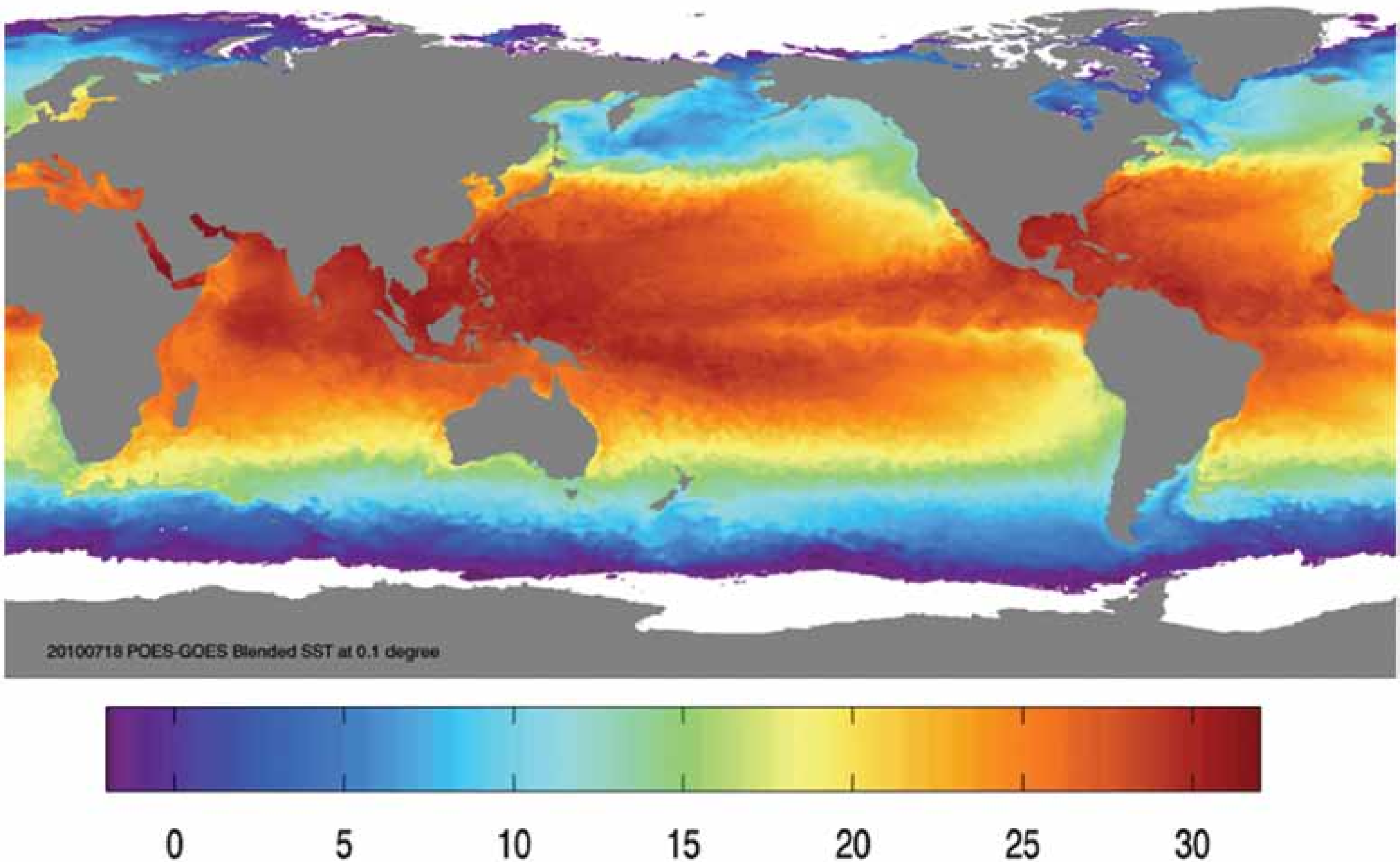
While geostationary satellites (GEOs) provide continuous observations, low Earth orbiting satellites (LEOs) carry more accurate thermal infrared (IR) instruments as well as microwave instruments for SST measurements. The microwave sensors have coarser spatial resolution (50 km) than the IR instruments (5 km). However, unlike IR instruments, microwave instruments on LEO satellites can see through clouds. Originally, separate SST maps were created independently from the GEO and LEO measurements.

STAR scientists have developed a system for merging the LEO and GEO observations into a consistent SST analysis that exploits the advantages of each type of satellite. The multi-scale analysis methodology collects the SSTs produced by each satellite on a daily basis, quality controls them for errors, removes the errors and then blends them to produce the best estimate of SST with no gaps.

The daily global multi-platform blended SST maps benefit weather, ocean and climate scientists who need a single reliable, consistent standard. SST variability is important in understanding and predicting monsoons and the onset of El Niño and La Niña as well as improving daily and weekly forecasts.

NOAA's Coral Reef Watch program is using these GEO-LEO blended analyses to generate new monitoring tools for detecting coral reef bleaching around the world.

Multi-Satellite Sea Surface Temperature Map



Sea surface temperatures (Deg C) on July 18, 2010 generated from merged polar and geostationary satellite data. Geostationary satellites: NOAA's GOES-E/W, Europe's Meteosat Second Generation (MSG), Japan's Multi-functional Transport Satellite (MTSAT); Polar Satellites: NOAA-19, Europe's MetOp-A. By merging polar and geostationary SST satellite retrievals a complete global map of SST is obtained each day without data gaps.

Ocean Surface Winds

Paul S. Chang and Zorana Jelenak

Ocean surface winds are a crucial piece of information in understanding and predicting the short-term and longer-term processes that drive our planet's environment. As the largest source of momentum for the ocean surface, winds affect the full range of ocean movement, from individual surface waves to complete current systems. Winds along the ocean surface regulate interaction between the atmosphere and the ocean by modifying the air-sea exchanges of heat, moisture, gases, and particulates. These interactions influence global and regional climates.

Satellite-borne radars are used to measure both the speed and direction of the wind – the Ocean Surface Wind Vector. The power of the radar signal reflected back to the satellite by the ocean surface depends on the strength of the capillary-gravity waves that are generated by the prevailing winds. Wind direction is obtained by viewing the surface at different angles. The QuikSCAT scatterometer provided more than a decade of high quality global ocean vector wind observations with better sampling than any other scatterometer. Its reliability, high quality, relatively fine spatial resolution, and large daily geographical coverage resulted in the largest impact of any scatterometry mission used for operational marine weather forecasting and warnings. And, for the first time, a number of satellite-based wind vector climatologies has been constructed to help characterize winds over the ocean.

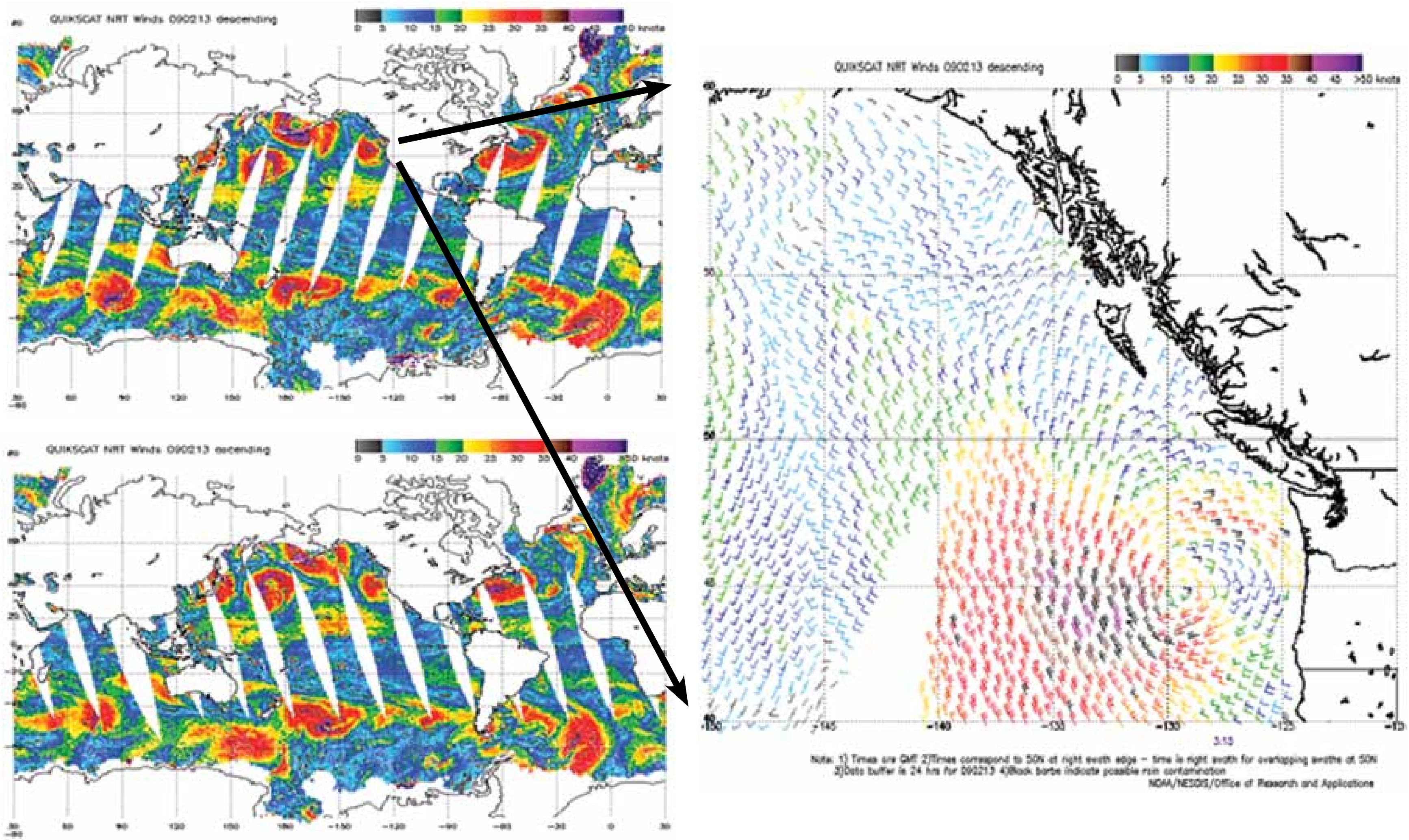
STAR scientists have developed and continue to improve the algorithms for processing the satellite observations and making them available in real-time to weather and ocean computer models and field forecasters.

Flying into storms

STAR scientists are usually not out in the field making their own measurements: they sit at their computers and analyze the observations made by satellite instruments. But to test new versions of scatterometer instruments and to help researchers better understand the ocean surface winds in powerful storms – including hurricanes – they sometimes leave their comfortable offices and fly into the hearts of storms. The aircraft-borne scatterometers provide unique data not otherwise obtainable. This information will lead to improved satellite scatterometers and, with increased understanding of storm winds, better weather forecasts in the future.

STAR scientist Paul Chang (standing), STAR Visiting Scientist Zorana Jelenak, and University of Massachusetts graduate student Joe Sapp on NOAA's P-3 aircraft. (Photo credit: NOAA)

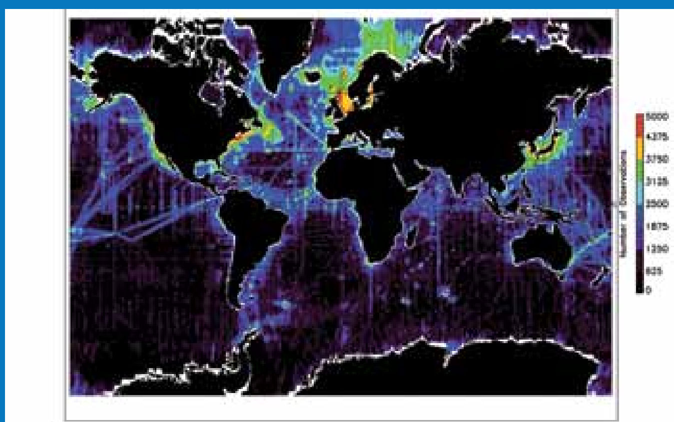
Daily Ocean Wind Coverage from QuikSCAT's Radar

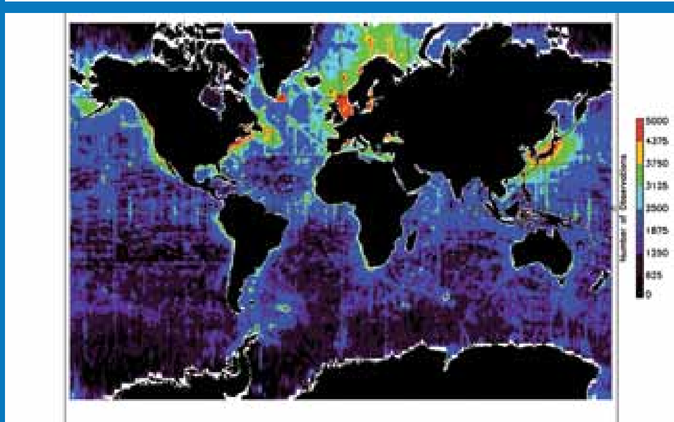


Left, an example of the daily ocean wind speeds (knots, with reddish colors representing highest wind speeds) from the QuikSCAT scatterometer. Left upper panel: nighttime observations; left lower panel: daytime observations. The broad 1800 km continuous orbital swaths covering 90% of the oceans each day coupled with QuikSCAT's high wind speed sensitivity made it extremely valuable for weather forecasts and warnings. The graphic on the right is a close-up view of QuikSCAT wind vectors using the wind barb notation off the Pacific Northwest coast. Red/yellow represents the strongest winds and green/blue the lighter winds.

Historical sea surface salinity (SSS)

NOAA's World Ocean Atlas 1998 (top) depicts the total number of SSS observations accumulated over the historical time period. The Argo float system, deployed over the next decade in conjunction with international partners, substantially increased SSS observations, as noted in NOAA's World Ocean Atlas 2009 (bottom). Note the significant areas of the world's oceans still with no observations ever (black regions).





Sea Surface Salinity

Eric Bayler

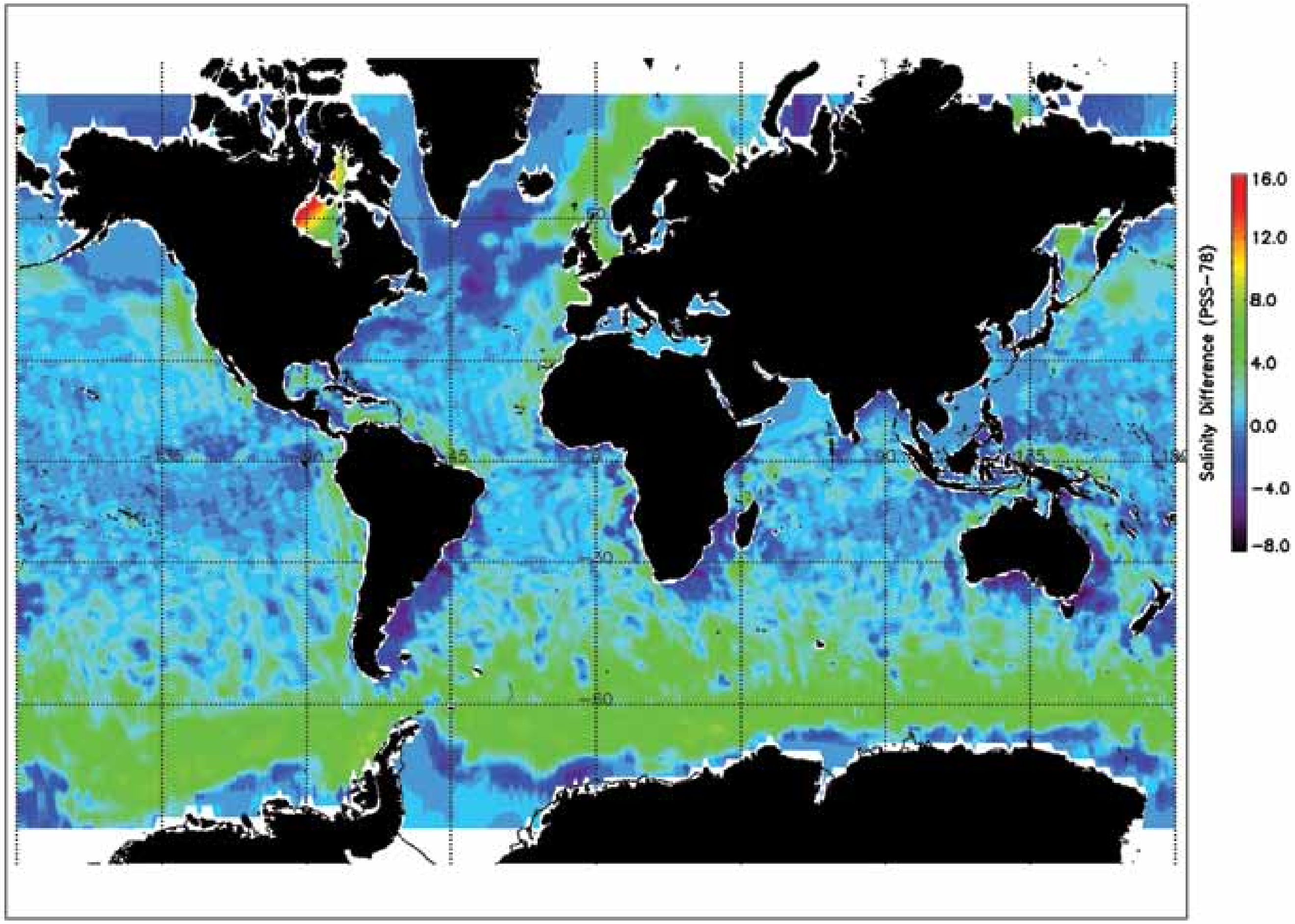
Salinity, the local concentration of salts in ocean water, can now be observed from space by the European Space Agency's Soil Moisture-Ocean Salinity (SMOS) mission and NASA's Aquarius mission. These new satellites provide near-simultaneous sea surface salinity (SSS) observations across the globe, yielding the first comprehensive assessment of the world's SSS and its variability. The satellites passively sense the ocean's emission of microwave energy, which is a function of salinity, temperature, and frequency, as well as surface roughness due to wind speed. The SMOS design, an entirely passive instrument, is a synthetic aperture interferometer. The Aquarius employs passive radiometers in conjunction with an active scatterometer.

Salinity, analogous to moisture in the atmosphere, is a primary characteristic of the ocean, combining with temperature to determine density. Density differences drive the ocean's thermohaline circulation, which governs much of the flow between the surface and the deep ocean. The ocean's thermohaline circulation responds to and drives climate-scale processes and variability. Near-term ocean modeling and forecasting will also benefit from improved SSS data, especially in the depiction of near-surface dynamics. Determination of upper-ocean heat content requires knowledge of altimetry, temperature, and salinity. In addition to climate-scale processes, the upper-ocean heat content governs, in part, the intensification of hurricanes.

The salinity information is also relevant to passive microwave remote sensing of other environmental characteristics because those measurements frequently depend on a representation of the energy emitted from the Earth's surface. Thus, satellite SSS observations have the potential for improving satellite observations of the atmosphere and improving numerical weather prediction.

STAR is developing and will provide the satellite SSS data sets and products for transition into operational use, as well as data quality analysis.

Difference Between Satellite Salinity Observations and Climatology



The difference between the mean satellite sea surface salinity observations for April 2011 and climatological averages highlights regions of potential bias due to the spatial and temporal sparseness of the data comprising the climatology. The sea surface salinity data are from the European Space Agency's Soil Moisture-Ocean Salinity (SMOS) mission, as processed by the SMOS Barcelona Expert Center. The climatology used for comparison is from NOAA's World Ocean Atlas 2009. In general, regions with apparently larger differences appear to be associated with significant ocean surface currents. Due to newness, the satellite sea surface salinity data used for this figure are still developmental and not fully validated.

Keeping ships away from trouble

Satellite observations of sea ice support the operations of NOAA, Navy, and U.S. Coast Guard vessels in, under, or near ice-infested waters, and are also used by the broader maritime community. (Photo credit: (top to bottom) NOAA, US Coast Guard, US Navy)

Sea Ice

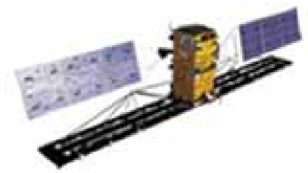
Pablo Clemente-Colón

Sea ice, or frozen ocean water, forms in the Polar Regions as well as in sub-Arctic regions, such as the Baltic and Yellow seas, as a result of decreased sunlight at high latitudes and extreme heat loss from the ocean surface into the atmosphere. Satellites afford a vantage point from which to routinely monitor daily, seasonal, and longer term sea ice changes in both hemispheres. Satellite imagery from diverse sources, including passive and active microwave, and visible and infrared sensors, as well as in-situ and model observations, are routinely processed and analyzed to characterize and monitor the sea ice cover. A similar analysis is done for lake (fresh water) ice over the Great Lakes. This information is transmitted to a wide number of operational and research users for applications ranging from ship navigation to weather forecasting, seasonal outlooks and climate research.

Increasing maritime operations in both the Arctic and Antarctic regions require maintaining and improving our capabilities to detect and characterize the presence of thick first year ice, multi-year ice, and icebergs (ice of land origin) for both safe navigation and the protection of the environment. The National Ice Center (NIC) ensures that ice analyses and forecasts based on the satellite observations are available to its wide user base that includes the Navy submarine and surface fleets, the National Weather Service and international weather services, NOAA marine living resources research and hydrographic survey vessels, U.S. Coast Guard (USCG) icebreaker operations, and National Science Foundation Polar research and logistic operations. The shipping, oil and gas, and cruise ship industries, academia, and recreational users also use the ice forecasts and analysis.

The National Ice Center is comprised of NOAA, Navy, and USCG components, and its Chief Scientist is a member of STAR.

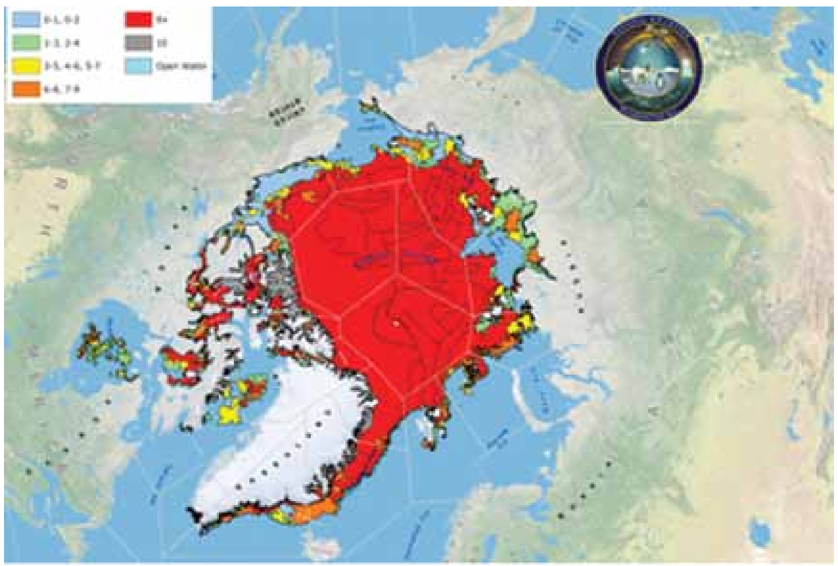
Different Satellite Sensors are used to Monitor and Chart Sea Ice

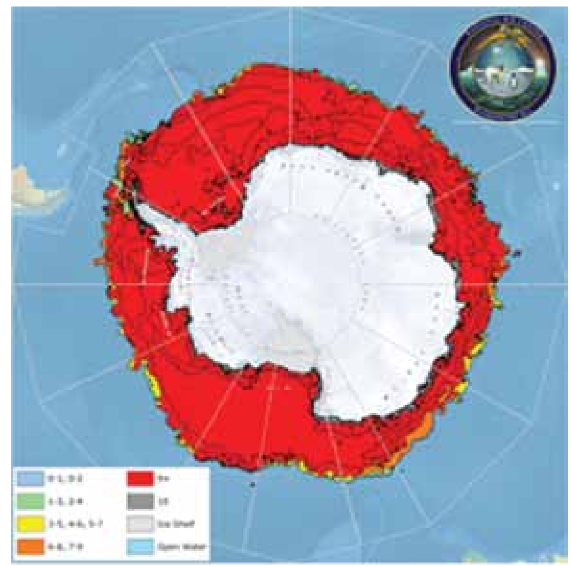


RADARSAT-2

POES

Envisat





Arctic Chart for 17-23 July 2011 (left); Antarctic Chart for 24-30 July 2011 (right)

Satellite sensors (upper panel) used by STAR for sea ice monitoring include synthetic aperture radars (SAR) aboard the Canadian RADARSAT and European Envisat satellites. Radar satellite observations can always see the ice since they can penetrate the clouds to the surface. Visible and infrared radiometers aboard the NOAA Polar-Orbiting Environmental Satellites also provide key observations in areas where there are no clouds. The combination of observation sources provides the best overall sea ice coverage.

Detailed charts (lower panel) depicting sea ice extent, type, and concentration (indicated in tenths by the colors in the charts, with red and grey representing the greatest sea ice concentrations) are produced from the analysis of the satellite observations.

Ocean Color Remote Sensing

Menghua Wang, Wei Shi and SeungHyun Son

The "color" of the ocean depends on the substances in the water, particularly phytoplankton – microscopic, free-floating photosynthetic organisms – and inorganic particulates. Satellite ocean color observations provide the only means to quantify changes in the global ocean biosphere, as well as on regional ocean scales, and over long time periods. Ocean color also helps scientists link biological changes to changes in the ocean environment. For this reason, chlorophyll concentration is a key parameter derived from the ocean color measurements.

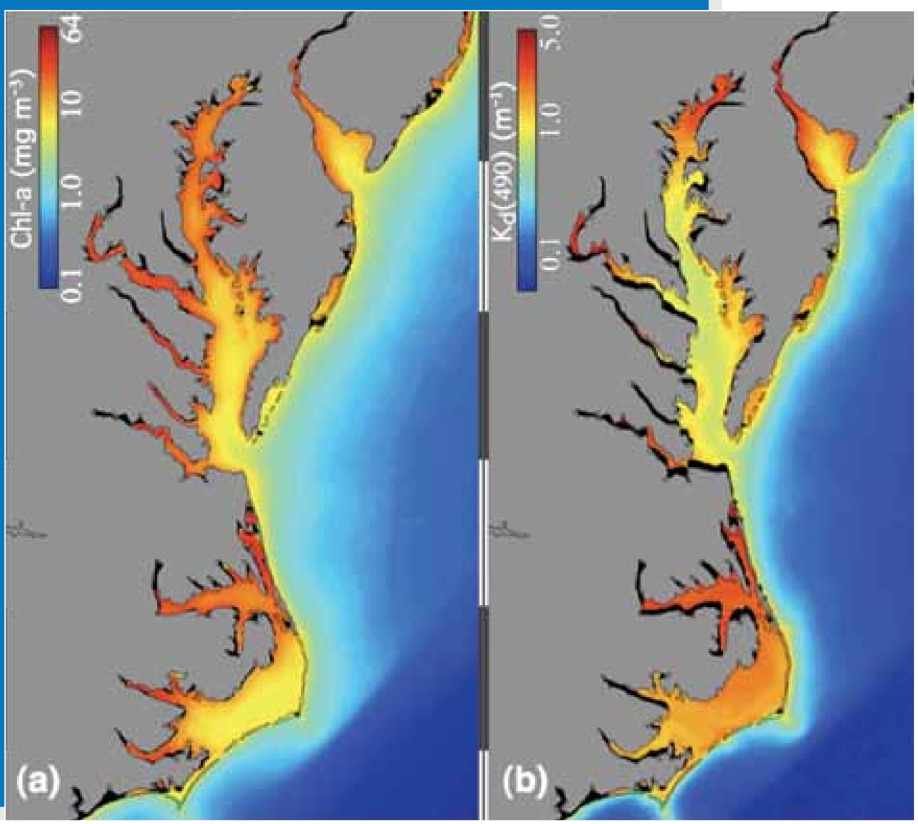
NASA's Coastal Zone Color Scanner (CZCS: 1978–1986) demonstrated that measurements of ocean color based on sunlight reflected from the water in the visible and near-infrared (NIR) spectral bands could be used to monitor ocean substances. Since the CZCS, a number of ocean color instruments have been flown on research missions. The first operational sensor – the Visible Infrared Imaging Radiometer Suite (VIIRS) – will be part of NOAA's next-generation polar satellite system, the Joint Polar Satellite System.

Usually less than 10% of the visible radiance measured by an ocean color sensor comes from ocean waters - the rest is sunlight scattered back to space by the atmosphere and sea surface. Detecting the weak ocean signal places very stringent requirements on the sensor's calibration and the algorithm that is used to correct for the atmospheric distortion. For open oceans, STAR has developed an atmospheric correction algorithm that uses the near-infrared (NIR) bands; for turbid coastal and inland waters, STAR's algorithm depends on the shortwave infrared (SWIR) band measurements.

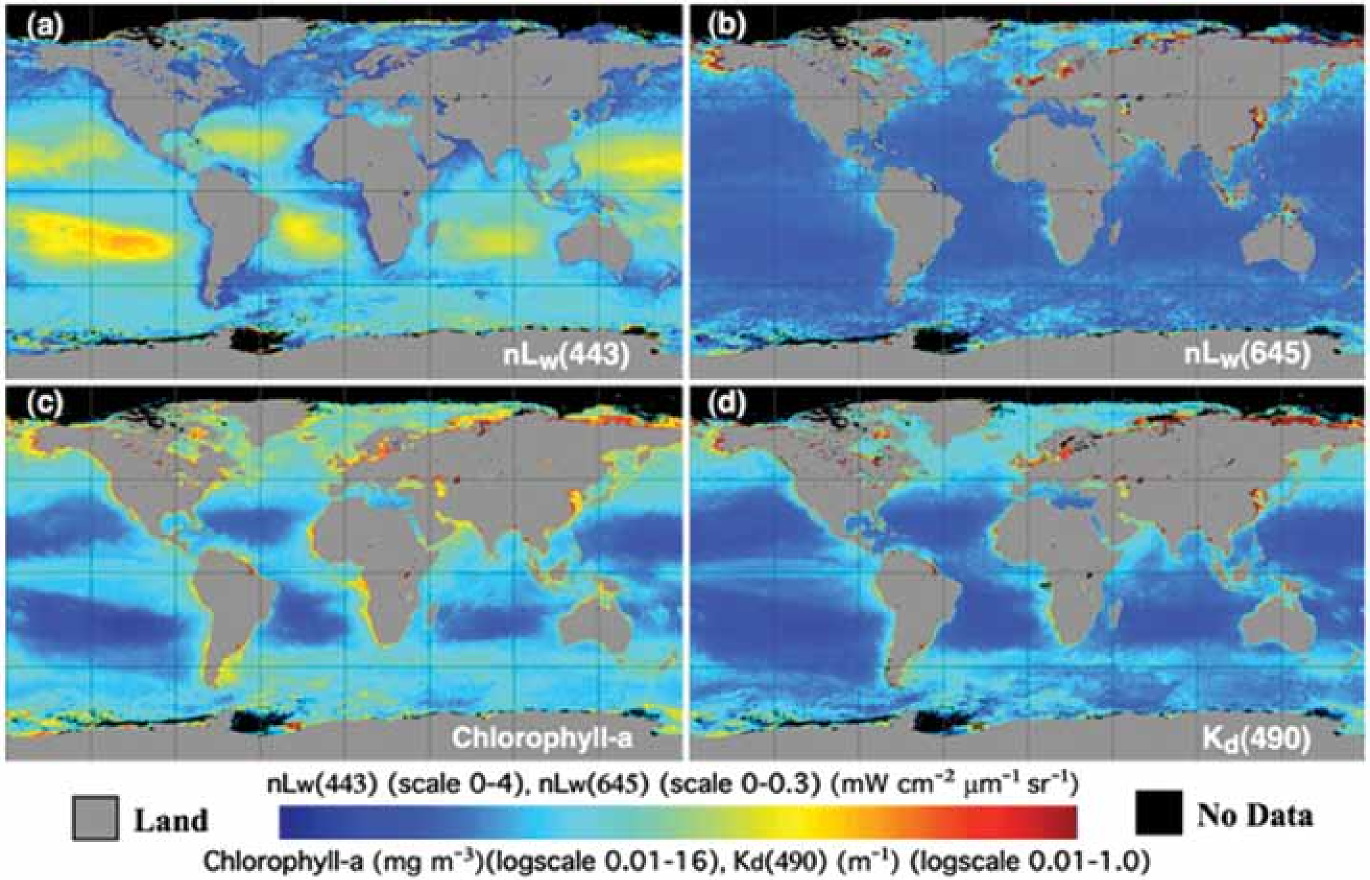
The ocean color measurements are used by the NOAA community for a wide variety of applications, including analyses of carbon cycling, detection and monitoring of harmful algal blooms, assessment of water quality, and the characterization of fisheries habitats.

Chlorophyll and sunlight penetration

STAR's atmospheric correction algorithm has been used to derive improved ocean color products along the U.S. east coastal region. Chlorophyll-a concentration (panel a) is an index of phytoplankton biomass which is a key ecological property in the aquatic system. Another product measures the murkiness of the water (diffuse attenuation coefficient shown in panel b) which provides information on light penetration and light availability. Satellite ocean color observations are critical for our understanding of ocean optical, biological, and biogeochemical processes and phenomena.



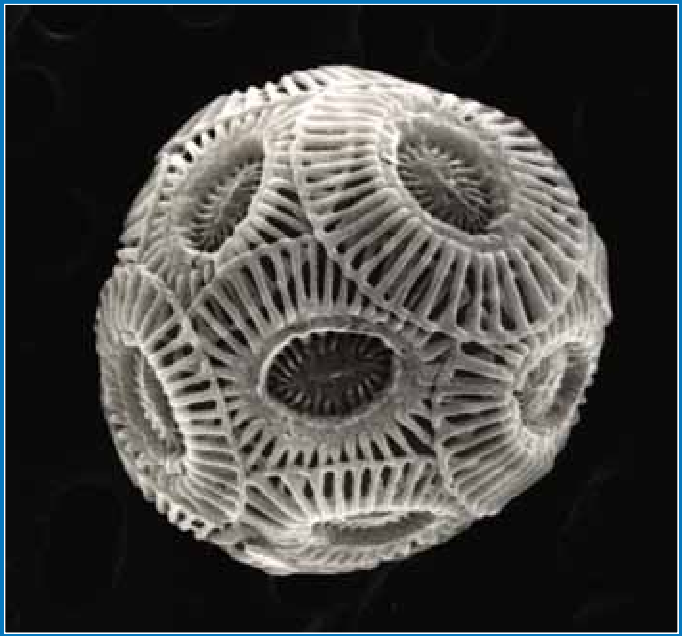
Biomass and Clarity of the Ocean



Global ocean optical and biological properties can be derived from satellite measurements. The figure shows color images for the global composite distribution of the MODIS-Aqua-derived normalized water-leaving radiance in panel a (at 443 nm wavelength (nLw(443)) and in panel b (at 645 nm wavelength (nLw(645)). Chlorophyll-a concentration is shown in panel c and diffuse attenuation coefficient (at 490 nm wavelength (Kd(490)) is shown in panel d. These results were derived using the near and shortwave infrared (NIR-SWIR) ocean color data processing. MODIS-Aqua measurements from January, April, July, and October of 2005 were used to make the images. Data scales are indicated in the color bar –linear for nLw(443) and nLw(645) and logarithmic for chlorophyll-a and Kd(490) – with data ranges indicated above and below color bar. Panel a shows inverse of chlorophyll and algae absorption, while panel b can be directly related to the water near-surface total suspended sediment. Reds indicate high values and blues low values. The global maps clearly reveal highly productive regions along coastal and near-shore ocean areas in panel b, c, and d, while panel a indicates regions of strong chlorophyll from phytoplankton and algae.

Phytoplankton, coccolithophores, and Emiliania huxleyi

Phytoplankton are microscopic, single-celled plants and form the base of the aquatic food web. Coccolithophores, an abundant and widely distributed component of marine phytoplankton, are golden-brown algae that possess external calcareous (calcium) scales called coccoliths. Scientists estimate that these organisms generate more than 1.5 million tons of calcite a year, making them the leading calcite producers in the ocean.The coccolithophore species Emiliania huxleyi is considered the most productive lime-secreting species on Earth.



Scanning electron photomicrograph of the coccolithophore Emiliania huxley.

Global Distribution of Coccolithophore Blooms

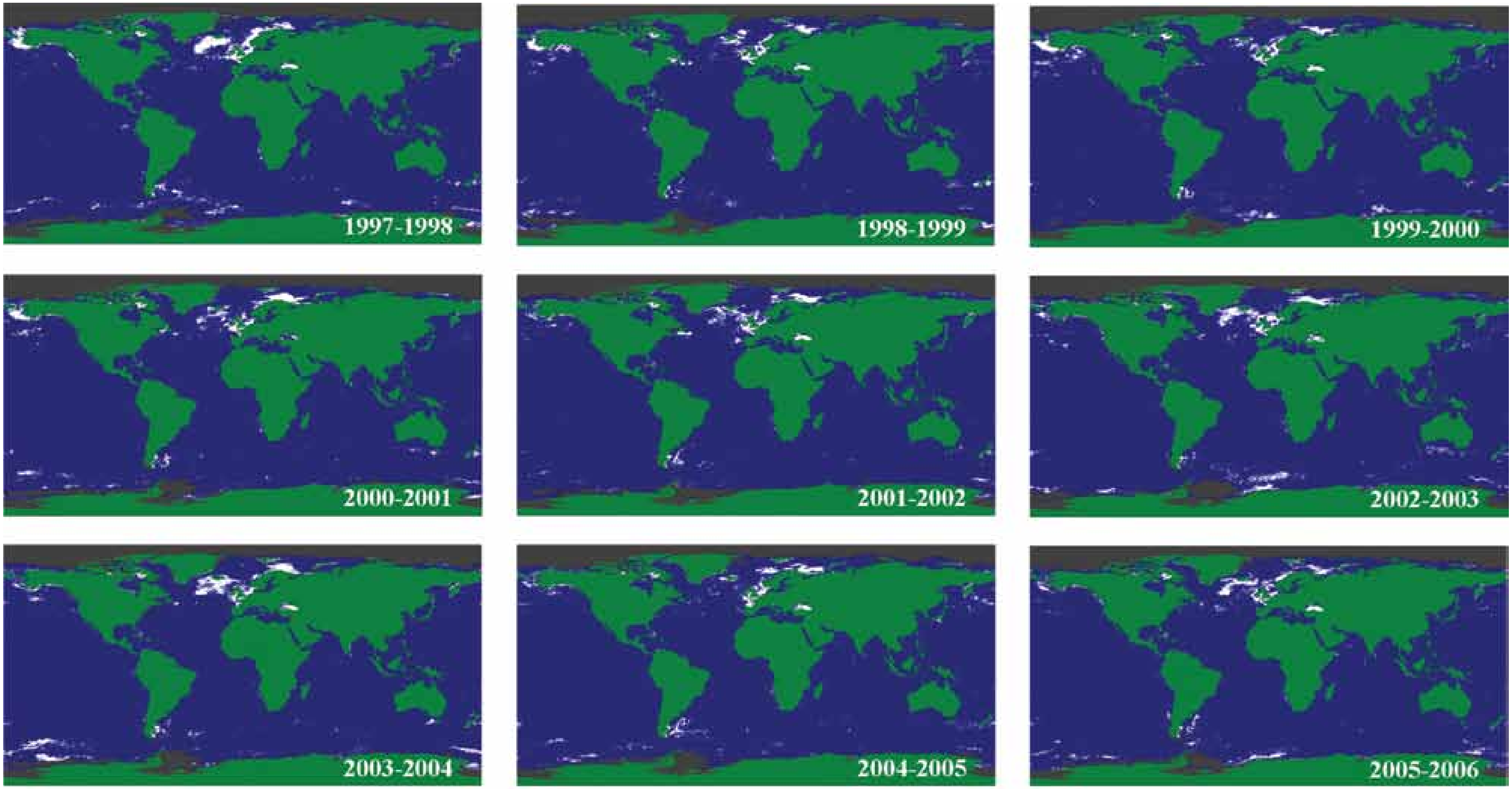
Christopher W. Brown

When oceanic conditions are favorable, high concentrations or "blooms" of the coccolithophores (see sidebar) can occur. These profoundly affect the biogeochemical and optical properties of the waters they occupy. Their presence modifies the chemistry of surface water through coccolith (calcium scale) and dimethylsulfide (DMS) formation. As the major calcifiers in the open ocean, coccolithophores alter the equilibrium of the inorganic carbon system and the alkalinity of seawater that can drive the outgassing of CO_2 to the atmosphere – which could modify the greenhouse effect – and the export of particulate inorganic carbon to depth. Coccolithophore blooms also impact higher levels of the food web, including fish, birds and marine mammals. For example, during the summers of 1997 to 2000, blooms of the coccolithophore Emiliania huxleyi blanketed the Bering Sea, resulting in high mortality rates of short tail shearwaters, and shifts in the distribution of many species, including the endangered right whales, and a reduction in local salmon runs.

Blooms of several coccolithophore species, particularly those of E. huxleyi, are detectable in visible satellite observations owing to the high reflectance of their coccoliths. These blooms are observed in satellite imagery at several locations, particularly in mid- and high latitude regions. Their high reflectivity reduces the solar heating of the oceans; any changes in the frequency or extent of these blooms could amplify or reduce greenhouse warming.

STAR scientists use satellites, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), to monitor the distribution pattern of the coccolithophore blooms on a regional and global scale in order to assess the magnitude of change in the marine ecosystem.

Interannual Variability of Coccolithophore Blooms



Annual composites of coccolithophore blooms during the first eight years of the SeaWiFS mission. Annual periods extend from October to September. The blooms are colored white, the ocean without blooms is blue, the land is green, and locations with no data are gray. Note the variability in the size of blooms located in the vicinity of Iceland from year to year, and the appearance of blooms in the Southern Ocean to the east of New Zealand in 2003-2004.

Satellite true color image of high sediment runoff in the Northern Chesapeake Bay

Following heavy runoff in the Chesapeake Bay in January 2010, sediments (muddy water inside oval) can be seen cascading down the bay from the Susquehanna River basin to over 40 miles south. The true color imagery is produced from a red, green and blue composite of MODIS Aqua bands 1, 3, and 4. (Photo Credit: NASA)

Coastal Water Quality

Michael Ondrusek and Eric Stengel

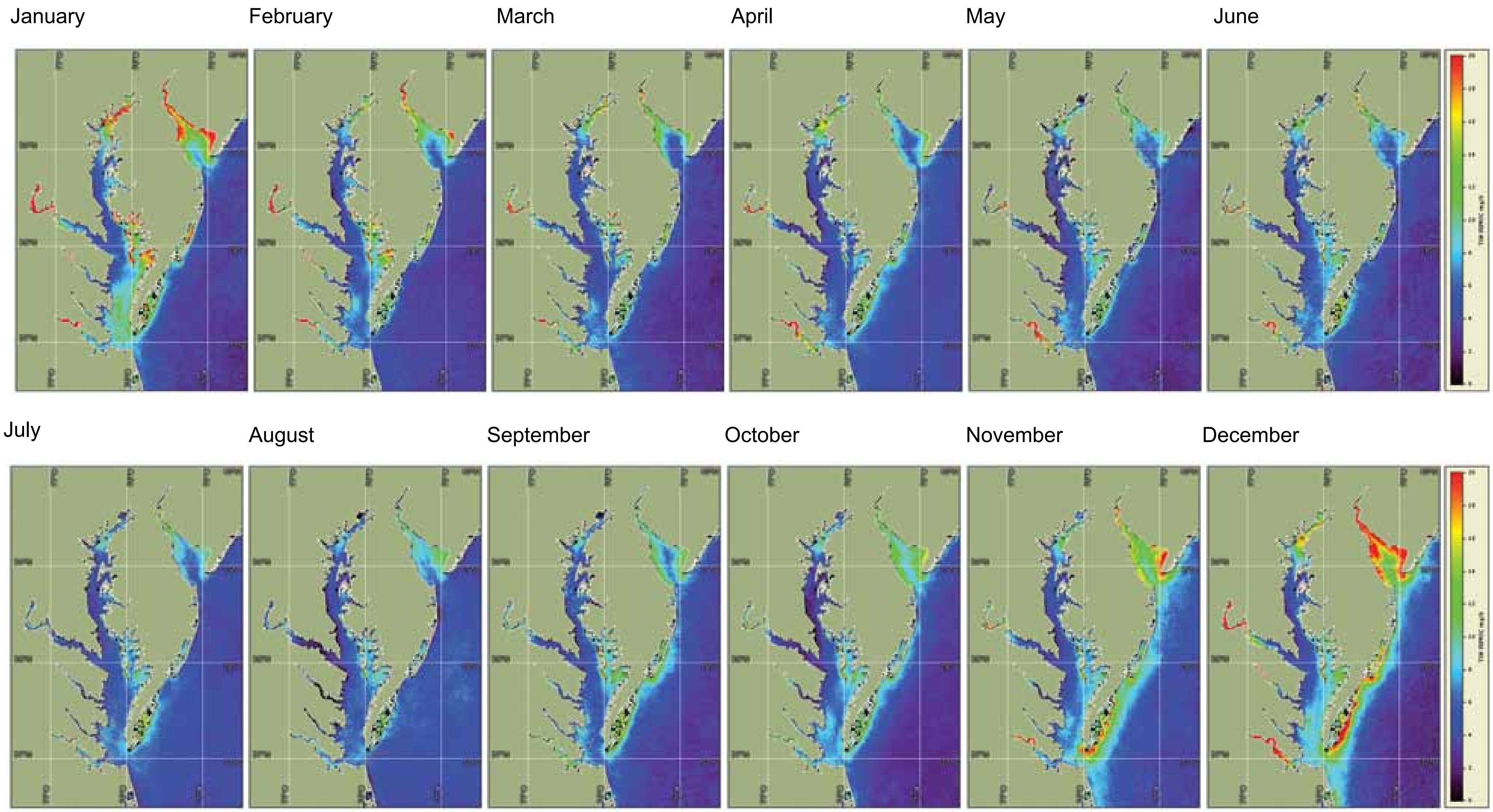
Using satellites to observe water quality in coastal regions has advantages over physical sampling and traditional monitoring techniques. Shipboard measurements are accurate and can provide observations at depth but are expensive and not continuous over space and time. Buoys provide good temporal coverage at one location but are isolated in space. Satellites expand the observations spatially for near-simultaneous measurements over a large area. An integrated sampling approach is best for monitoring water quality in coastal regions.

Satellite detection of water quality is limited to items that have an electromagnetic signature that can be observed by existing sensors. Particulate and dissolved colored material can be detected and quantified by ocean color sensors through algorithms that relate their concentrations to light emitted from the water. STAR uses these relationships to monitor runoff and its consequences over time and relay these findings to decision makers who regulate sources of these pollutants.

The Chesapeake Bay is the nation's largest estuary and is located in a highly populated region. Industrial and urban pressures have degraded the bay ecosystem. Increased agricultural and human land use has resulted in high sediment and nutrient runoff with detrimental effects in the bay. Sediments reduce light available to submerged aquatic vegetation and reduce habitats for oysters and other organisms. Increased nutrient fluxes are generally associated with these runoff events. The increased nutrients cause increased phytoplankton growth; their decay deprives the water column of the oxygen that is essential for the survival of all economically important marine organisms.

STAR investigators have developed satellite remote sensing tools to monitor runoff of Total Suspended Material (TSM) and other water quality indicators. These tools are used to support Chesapeake Bay monitoring and restoration efforts.

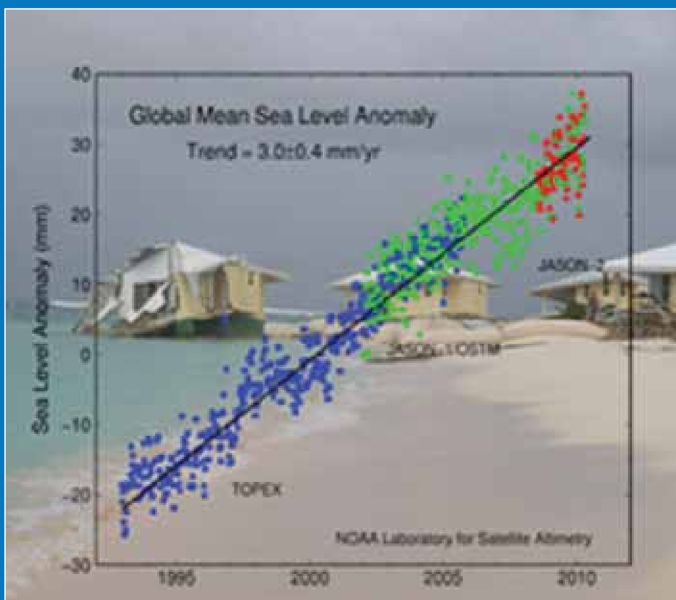
Total Suspended Matter in the Chesapeake Bay



Satellite monitoring of total suspended matter (TSM) in the Chesapeake Bay for 2009. Each image is a monthly average demonstrating the ability to quantify seasonal variations of runoff into the bay. Concentrations are in milligrams per liter (mg/l), with red representing the muddiest water, and the spatial resolution is 250 m. In 2009, highest monthly averaged TSM concentrations were observed in the northern Chesapeake Bay in January. The explanation of seasonal variability in TSM is complicated but can be tied to increased river discharge, sediment resuspension and erosion. All three causes can be related to storm and precipitation activity.

Sea level rise: Climate change or natural variation?

Observations from three overlapping TOPEX/Jason satellite radar altimeter missions, collectively the international Committee on Earth Observation Satellites (CEOS) Reference Mission, show an almost steady increase in sea level of 3.0 mm/yr, nearly twice the historical rate of 1.7 mm/yr estimated from coastal tide gauges over the past century. Whether the present higher rate reflects an acceleration related to global warming or natural, multi-decadal variability is yet to be determined.



The TOPEX/Jason series was initiated by NASA and the French National Center for Space Studies (CNES); however, beginning with Jason-3 the series will be jointly managed by NOAA and EUMETSAT, with NASA and CNES in supporting roles.

The Ocean Surface Topography Satellite Constellation

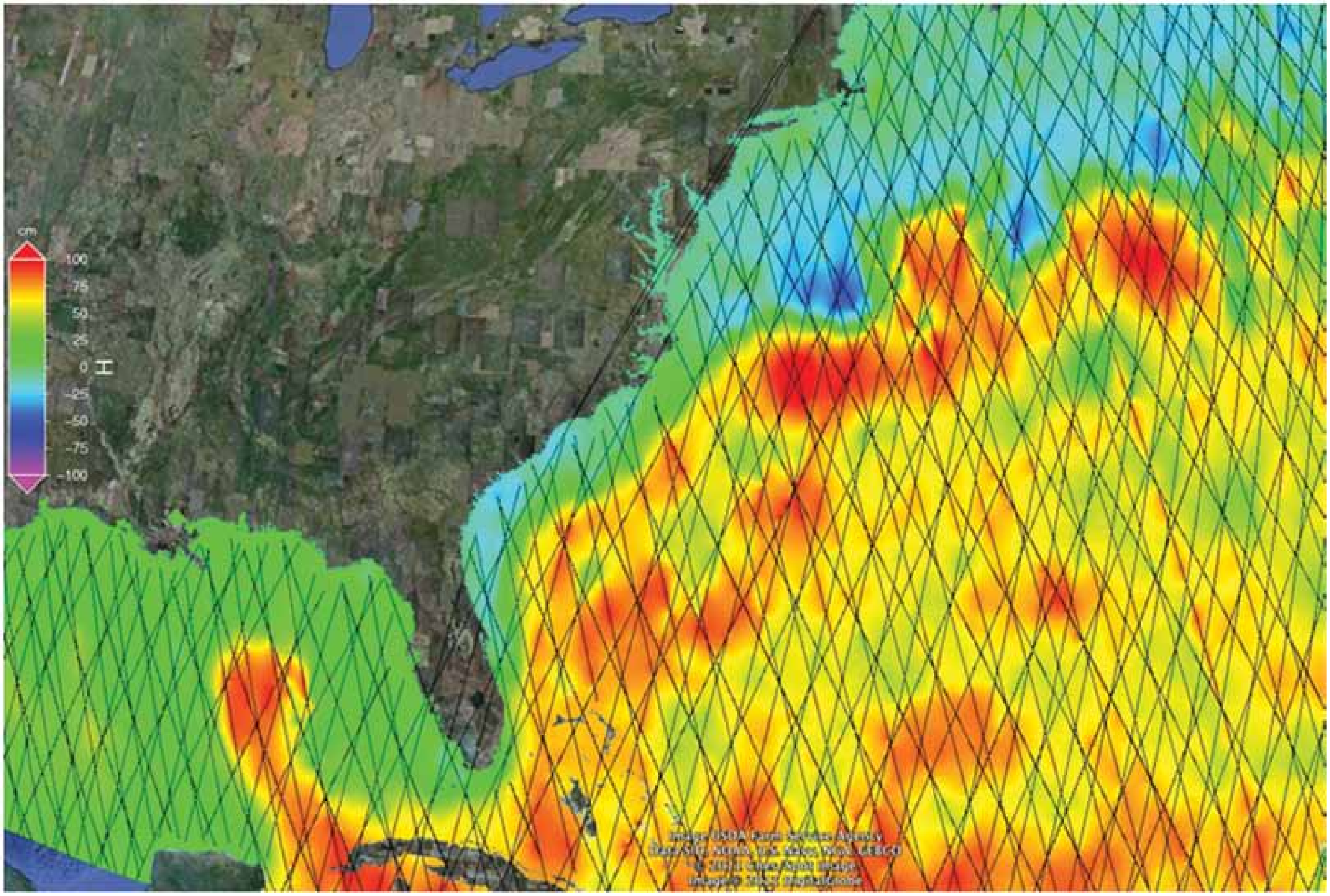
Laury Miller

Satellite radar altimeters map sea level features globally by precisely measuring the difference between a satellite's altitude and the distance between the satellite and the sea surface. However, present radar technology only provides point "looks" at the ocean along a satellite's ground track that typically has a repeat sampling interval of 10 to 30 days. The spacing of adjacent ground tracks between orbits is a couple of 100 kilometers. Clearly one satellite radar altimeter is not enough for these measurements.

To deal with this challenge, the Committee on Earth Observation Satellites (CEOS), a 40-nation organization including the U.S., France, Germany, India, and China, has established a program to coordinate on-going and future radar altimeter missions. The principal goals are threefold. The first and highest priority is to ensure continuity of the more than 20-year old, high-accuracy TOPEX/Jason reference mission that forms the basis for the sea level climate data record. The second goal is to maintain at least two additional medium-accuracy altimeters for sampling meso-scale (100 km horizontal scale) ocean variability. The third goal is to encourage innovation.

STAR personnel are currently serving as NOAA Program and Project Scientists for several satellite altimetry missions. Using the data from the satellite altimeters, the sea level rise of the Earth's oceans can be monitored.

Ocean Features Revealed by Constellation of Three Satellite Altimeters



The average ocean surface topography off the U.S. East Coast measured by the Jason-1, Jason-2 and ENVISAT satellite radar altimeters between 23 March and 21 April 2011. Solid black lines are the tracks of the satellite observations. The sharp boundary between red and blue areas marks the location of the Gulf Stream running along the Southeast Coast and then eastward from Cape Hatteras. The presence of eddy-like features scattered throughout the Sargasso Sea (east of the Gulf Stream) and the narrow structure of the Loop Current in the Gulf of Mexico highlight the need for having a constellation of radar altimeters to adequately sample meso-scale (~ 100 km) variability in the ocean.

Aliasing of Altimeter Observations

C. K. Tai

Without a sufficient number of observations of a physical phenomenon (as is usually the case for ocean remote sensing), the resulting analysis of the measurements may suffer from artifacts. This effect is called aliasing in sampling theory (see sidebar). A simple example is provided by the silent-film-era movie. In those times, the movie camera was not fast enough to take many pictures per second. If a bicycle was filmed moving forward, the bicycle wheels often appeared to rotate backwards instead, especially for fast riders. This is a classic illustration of the phenomenon of aliasing.

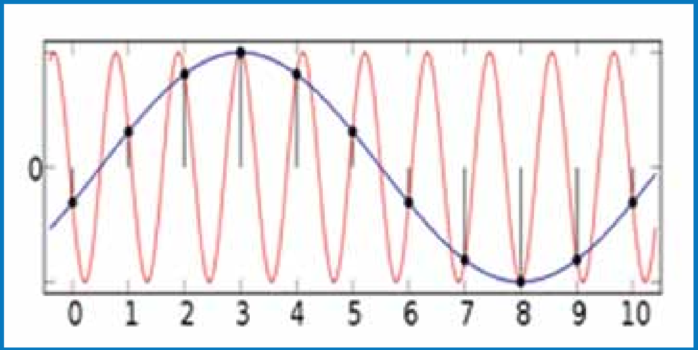
When one measures the sea surface height using a satellite altimeter that observes each point on the ocean only once every 10 days, one clearly does not have enough measurements to avoid the aliasing phenomenon, especially for fast changing ocean features (see illustration opposite page). Moreover, if one were to measure the sea surface height with more than one satellite, one has to coordinate the satellites in a way to optimize the sampling characteristics, that is, to avoid the aliasing as much as possible, and thus avoid being fooled.

STAR scientists have studied these issues for many years and developed the best ways to process the data to reduce aliasing.

Scientists fooled by aliasing

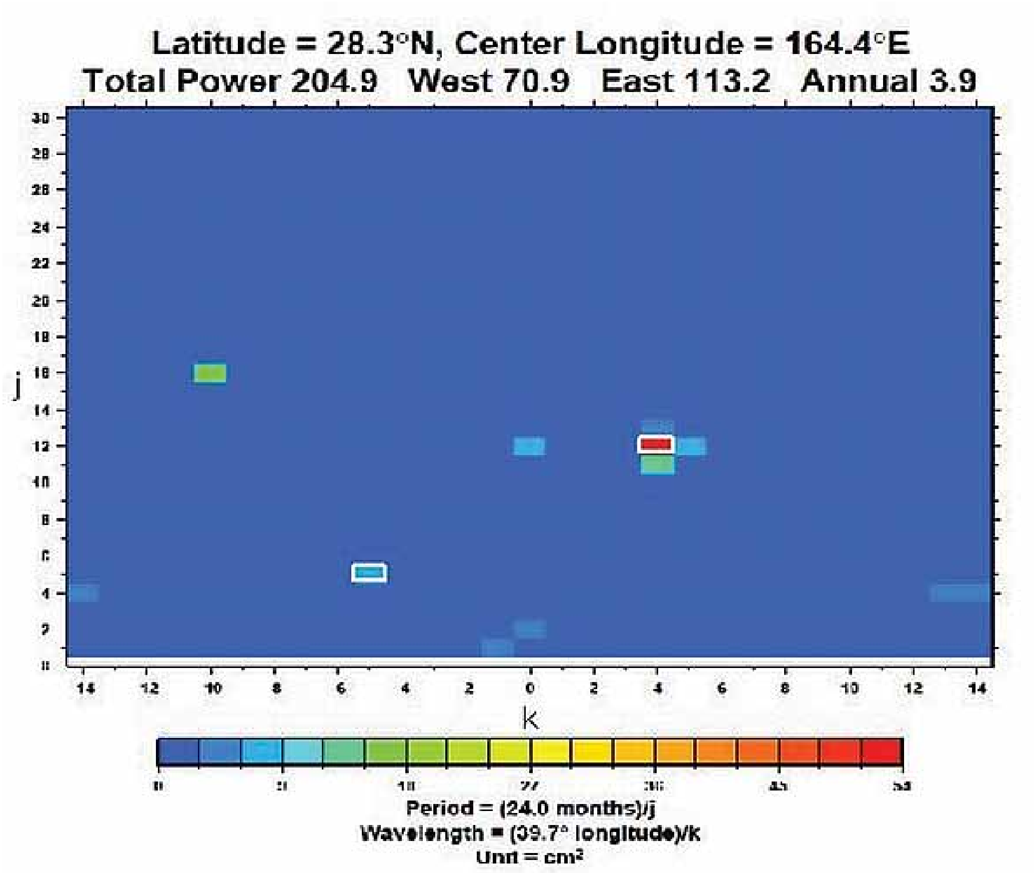
In the illustration below, the signal is the red curve. Observations are made at fixed intervals of time marked by 0, 1, 2, etc. The blue curve is the result of connecting the observation points. Instead of the true signal represented by the red line, the observations appear to represent the blue line. This is the basic concept of aliasing. It is clearly caused by not observing frequently enough.

In the published peer-reviewed scientific literature, there are examples of aliased results being interpreted as real results. These are not only embarrassing, but can lead the scientists to pursue illusory goals, thus wasting talent and funding. It is important for all scientific observers to be cognizant of aliasing.



(Photo credit: Aliasing in Wikipedia. Retrieved November 29, 2012 from http://en.wikipedia.org/wiki/Aliasing); Image author Moxfyre

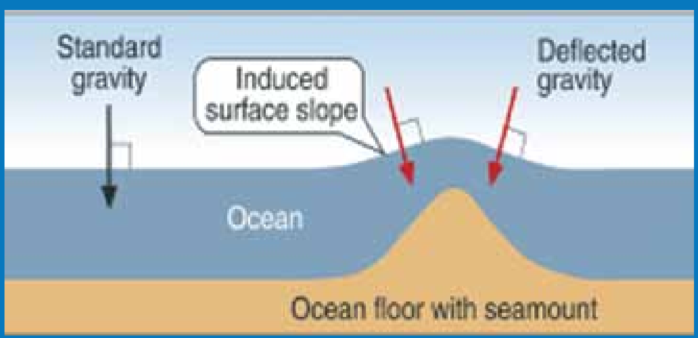
Tidal Aliasing in Theory and Observations



The zonal-wavenumber (x-axis) and frequency (y-axis) spectrum of alitimetric sea level over about two years in 1994 and 1995, at 28.3°N, from 144.6 to 186.3°E in the North Pacific. The tides have periods (about half a day to a day) shorter than the 20 days that the repeat altimeter observations at 10 days apart are able to resolve. They are aliased into periods of about 2 months with a wavelength about 10° longitude as predicted by the aliasing theory (see the red rectangle with white outline at j=12 and k=4), and thus can be discounted as fictitious. The largest real signal in the spectrum is at j=5 and k=-5 (blue rectangle with white outline), representing an oceanic wave (called Rossby wave), which is instrumental in ocean dynamics. The remaining colored rectangles represent either aliasing of other tidal components or real signals. Note that a spectrum separates the signal into its spectral components at various frequencies and wavenumbers (i.e., wavelengths) and gives the power at each spectral component, just as the sunlight can be separated into various colors and even more frequencies (from ultraviolet to infrared, for example).

How sea level reveals the sea floor

Satellite altimeters measure sea level from space. The height of the sea level with respect to a reference ellipsoid varies from place to place and time to time. Time-varying height changes are due to tides, meandering currents and eddies, winds and atmospheric pressure, and climate changes. But sea level also has permanent bulges and hollows caused by variations in the pull of gravity due to undersea mountains and valleys. Where a mountain displaces water, its extra mass increases the pull of gravity nearby, pulling extra seawater around the mountain and bulging the sea outward. The height of this bulge can be 1 meter or more. After the time-varying sea level signals are removed, the remaining constant level shows these bulges. The tilt of the sea level can be used to calculate the gravity anomaly, which can then be verified by ships carrying gravimeters. Satellite altimeters have resolved these tilts to a few micro-radians, fine enough to reveal most of the plate tectonic features of the ocean floor.



Mapping the Global Ocean Floor from Space

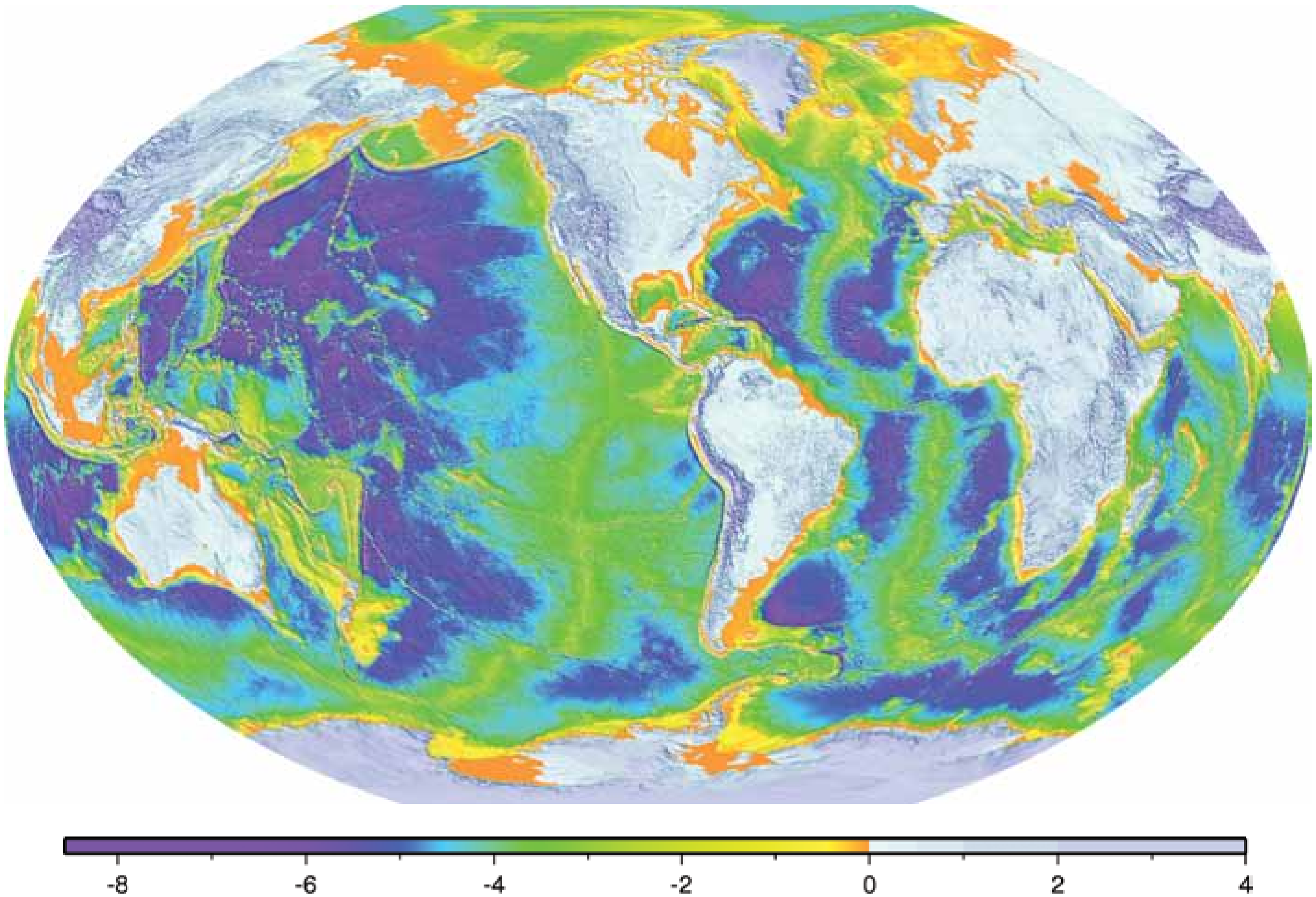
Walter H. F. Smith

Most of the Earth's surface is ocean more than 200 miles from any coast, and beyond the mapping responsibilities of coastal nations. Only a small percentage of this vast area has been surveyed. The paths taken by bathymetric (depth measuring) survey ships cover the remote ocean about as sparsely as the Interstate Highway System covers the United States.

Tsunami forecasts, ocean circulation and climate models, fisheries and habitat management, and many other applications – including the laying of transoceanic telephone cables (in fact, this author's first cruise at sea was funded mostly by AT&T for a trans-Pacific cable survey) – need a map of the depth of the global ocean floor. The shape of the bottom steers the flow of currents, while the roughness of the bottom controls mixing rates. Seamounts (undersea mountains, volcanic in origin) produce upwelling water and provide rich habitats. An estimated 100,000 seamounts more than 1 km tall have yet to be discovered.

Satellite radar altimeters measure the elevation of the ocean surface. Although the radar cannot "see" through to the ocean floor, subtle slopes in the ocean surface height reveal the gravity anomalies induced by topography below. STAR scientists have led the development of the technique which translates ocean surface slope into bottom topography details, which has been validated by scientific and military surveys worldwide. The method has only moderate resolution – mountains on the seafloor need to be about 10 km wide and 2 km tall in order to generate enough gravity anomaly to be detected in presently available measurements – and so will not supplant traditional acoustic echosounding. Even so it furnishes the background view (e.g., in Google Earth) and the global framework into which more detailed surveys may be placed.

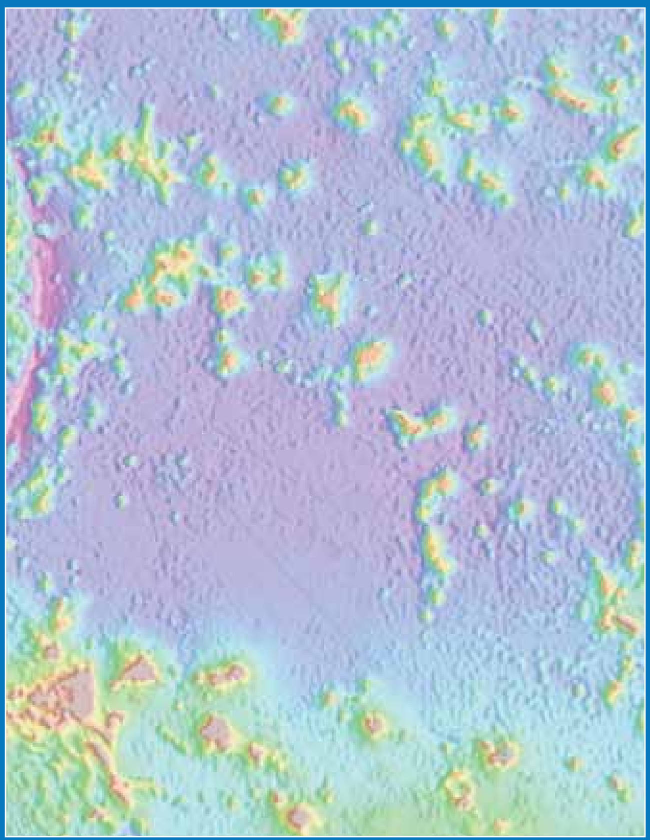
Global Sea Floor Topography from Satellite Altimetry



Satellite altimetry has revealed the tectonic fabric of the sea floor. The mid-ocean ridges (yellow-green) are the longest, and in places, most rugged, mountain ranges on Earth. Earth's tallest mountains are the volcanic islands, like Hawaii, that rise from the sea bed four or more kilometers below sea level. Nearly all of Earth's active and dormant volcanoes are on the ocean floor. Tides rubbing against the rugged ocean bottom dissipate energy at rates of a few terawatts (1 terawatt = 10^{12} watts), equivalent to the rate at which winds do work on the sea surface. The shape of the bottom is thus fundamental to modeling the mixing and circulation of the ocean.

How deep is the ocean?

Depths shown on this User's Guide for General Bathymetric Charts of the Ocean cover the range from shallow seamounts (orange) to more than 7000 m deep (purple) in the Mariana Trench (upper left).



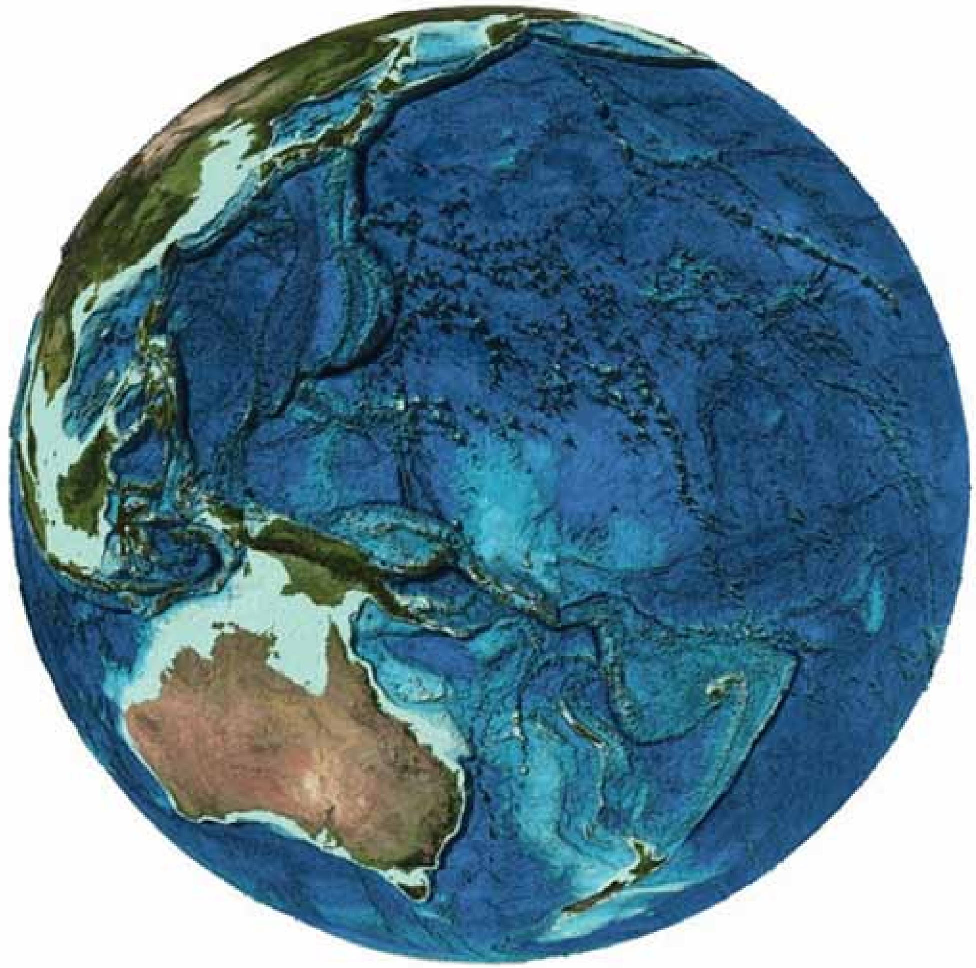
International Efforts to Improve Global Ocean Depth Map

Karen Marks

General Bathymetric Charts of the Ocean (GEBCO), which emerged from a commission chaired by Prince Albert I of Monaco in 1903, aims to provide the most authoritative publicly-available global bathymetry data sets of the world's oceans. It has grown into an international organization with more than 80 member states that operate under the auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO. The current GEBCO data grid is based on a NOAA altimetric bathymetry model that combines seafloor depths derived from satellite gravity data with in-situ data such as soundings and shorelines, the International Bathymetric Chart of the Arctic Ocean (IBCAO) grid, and other data. STAR works to continuously improve the NOAA altimetric bathymetry model.

STAR is playing a leading role in the GEBCO "Cookbook" Working Group, which is writing a user's manual to guide nascent regional mapping projects. The Cookbook will be a technical reference manual on the development of bathymetric grids and will include step-by-step instructions that users can follow to produce high-quality grids from their own data sets and then submit them for incorporation into the GEBCO global grid. The Cookbook will also cover topics such as data cleaning, metadata (description of the data) documentation, various gridding methods, testing, and uncertainty assessments.

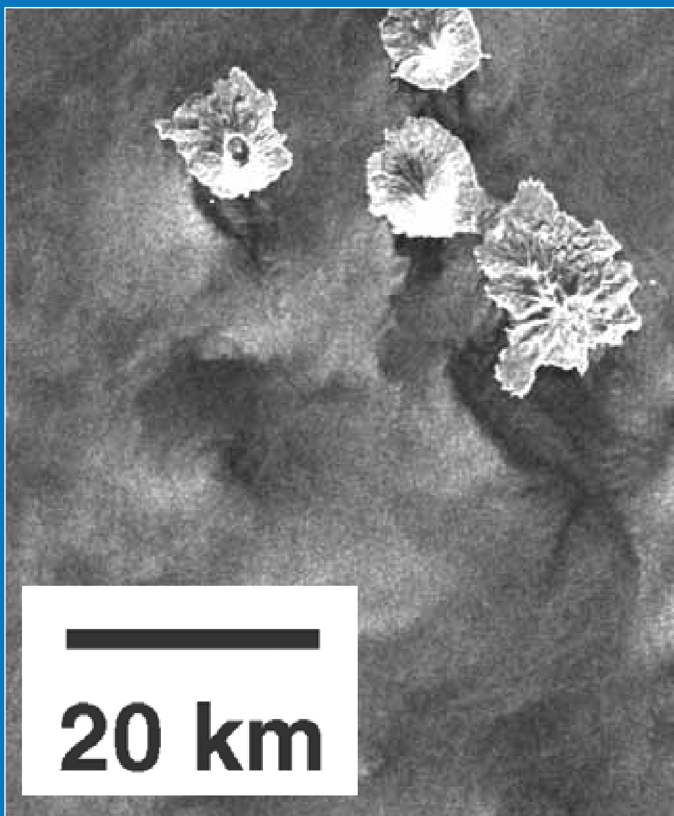
Western Pacific Ocean Depths from Combined Ship and Satellite Observations



3-D view of GEBCO global ocean depth map, centered on the Pacific Ocean (lighter blue colors, shallower; darker blue colors, deeper). GEBCO_08 is a global 30-arc second (about 1 km) grid based on quality-controlled ship depth soundings and estimated depths from the NOAA altimetric bathymetry model, plus other bathymetric datasets. The GEBCO User's Guide provides a manual for regional mapping efforts to produce and test high-quality grids that may be incorporated into the GEBCO global bathymetry grid. (Photo credit: http://www.gebco.net)

Atmospheric vortex streets

Sea surface roughness changes associated with ocean and atmospheric phenomena can be imaged by SAR with very high spatial resolution in all weather conditions, day or night.



The figure shows the imprint on the sea surface (light and dark areas coming down the page) of an atmospheric vortex street – a double row of opposite rotating, mesoscale eddies – off the Aleutian Islands (top of figure) imaged by the RADARSAT-1 SAR (© CSA 1999).

Oceanic and Atmospheric Features from Synthetic Aperture Radar

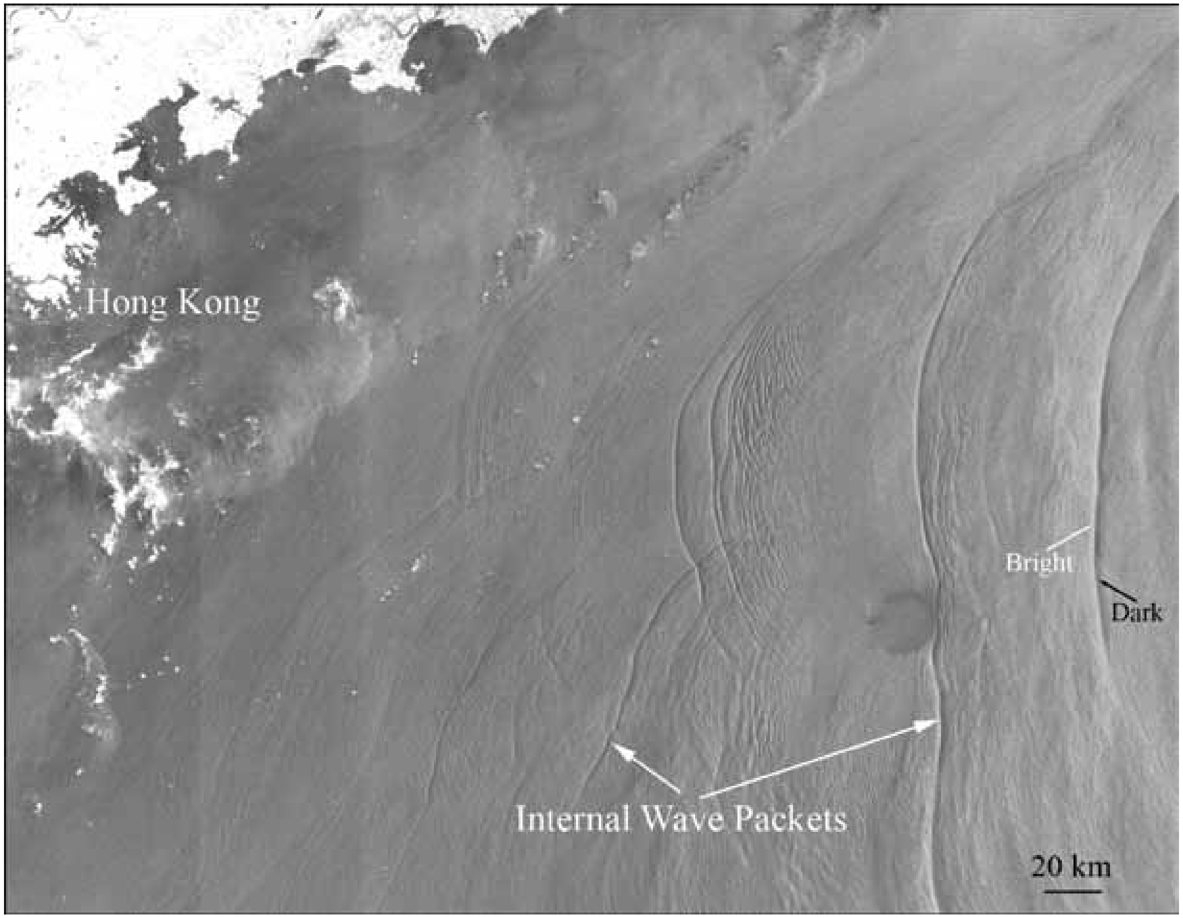
Xiaofeng Li and William Pichel

Wide-swath synthetic aperture radar (SAR) active microwave instruments observe the large-scale ocean surface in unique ways. Modern satellite SAR instruments can actively monitor phenomena in the coastal ocean and marine atmospheric boundary layer (MABL) at very high spatial resolution (tens of meters) in all weather conditions, day and night. SAR is particularly useful in coastal regions where clouds are usually present, causing observation problems for visible and infrared sensors. The ScanSAR/Wide-swath SAR can provide coverage of about 450 km perpendicular to the satellite orbit, wide enough to discern oceanic and atmospheric meso-scale features. Any physical processes in the MABL and ocean column that change the surface wind and currents will change the sea surface roughness, leave an imprint on the ocean surface, and change the backscatter signal measured by SAR.

Studies have shown that SAR observations combined with theoretical and/or numerical models can lead to better weather forecasts. NOAA and other scientists have taken advantage of SAR observations to study hurricanes, atmospheric vortex streets (shown in sidebar), down-slope coastal mountain winds, atmospheric gravity waves (vertical atmospheric waves), atmospheric roll vortices (horizontal convective rolls), internal waves, and shallow and deep-water bathymetry, which are examples of phenomena important for navigation and safety of aviation and shipping, and coastal management.

With the increasing number of SAR sensors available today and near-future operational SAR satellites (Europe's Sentinel-1 and Canada's RADARSAT Constellation Mission), researchers and other users will have more repeat SAR observations of these ocean and MABL features with multiple radar frequencies and polarizations, resulting in more accurate environmental measurements. STAR scientists continue to explore and develop new applications using SAR data.

Synthetic Aperture Radar Captures Signatures of Internal Ocean Waves



A wide swath mode image (415 km × 330 km) acquired from the European Space Agency's ENVISAT ASAR (Advanced SAR) at 2:13 UTC 12 August 2009 shows alternating bright-dark features, which are sea surface imprints of tide-generated internal wave packets propagating from the Luzon Strait (400 km east of the center of this image) westward in the South China Sea. These internal wave packets are separated by tens of kilometers with amplitudes over 100 m. (©ESA 2009)

High-Resolution Coastal Winds

William Pichel, Frank Monaldo, and Xiaofeng Li

Winds have been derived from satellite remote sensing data for many years, beginning with cloud-drift winds in the troposphere from visible and infrared imagery picture pairs, and progressing to sea surface winds from passive microwave sensors and active microwave scatterometers. The most recent sensor to be used for wind measurement is synthetic aperture radar (SAR). SAR instruments are active microwave sensors similar to scatterometers, and like scatterometer observations, increases in radar backscatter are related to increasing wind speeds. Scatterometers have the advantage of also measuring wind direction and providing quasi-global daily coverage, whereas SAR instruments have the advantage of very high spatial resolution (approximately 0.5 km vs. 10 to 25 km for scatterometers) and the ability to measure winds right up to the coast and in straits, bays, and larger lakes. Wind accuracy for SAR winds is 1.5-2.5 m/s, on the order of scatterometer accuracy.

SAR measurements reveal the highly variable wind field along coasts with rugged topography, such as in the states of Alaska and Washington. Down-slope (i.e., katabatic) winds, barrier jets, and gap winds can result in dangerously high winds in one area, with benign wind conditions close by – a situation very difficult to forecast when employing only traditional satellite wind measurements. These phenomena are well depicted in SAR wind imagery, such as that shown in the accompanying figure.

National Weather Service meteorologists of the Alaska Region have requested that SAR winds be transitioned from a research mode to a real-time operational activity. Although SAR wind measurements to this point have relied on commercial and research satellites, the first of a constellation of five operational SAR satellites is scheduled for launch in the near future. STAR is developing the algorithms to be used in the real-time processing of the data from these satellites.

SAR coastal wind climatology applications

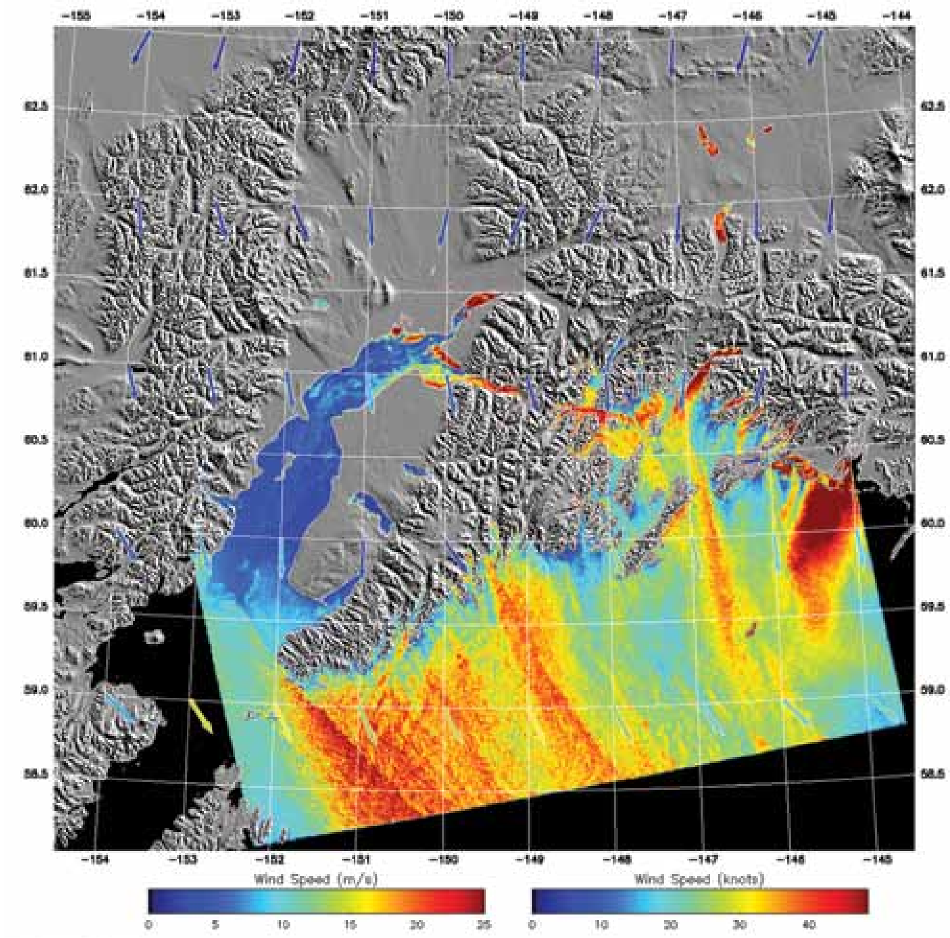
In addition to the use of SAR-derived wind measurements in near-real-time weather forecasting, some important climatological applications have emerged

SAR coastal winds are proving to be of value to the offshore wind energy generation industry. Long-term averages of high-resolution winds can indicate the best sites for establishing wind farms and how wind turbines affect the wind field for current or future turbines located downwind.

In addition, coastal winds determined from SAR imagery have been correlated with weather conditions to derive a statistical relationship that can be used to predict what the coastal wind conditions are likely to be for a given weather situation.

Wind turbines off the coast of Barrow, UK.(Photo credit: NOAA Fisheries)

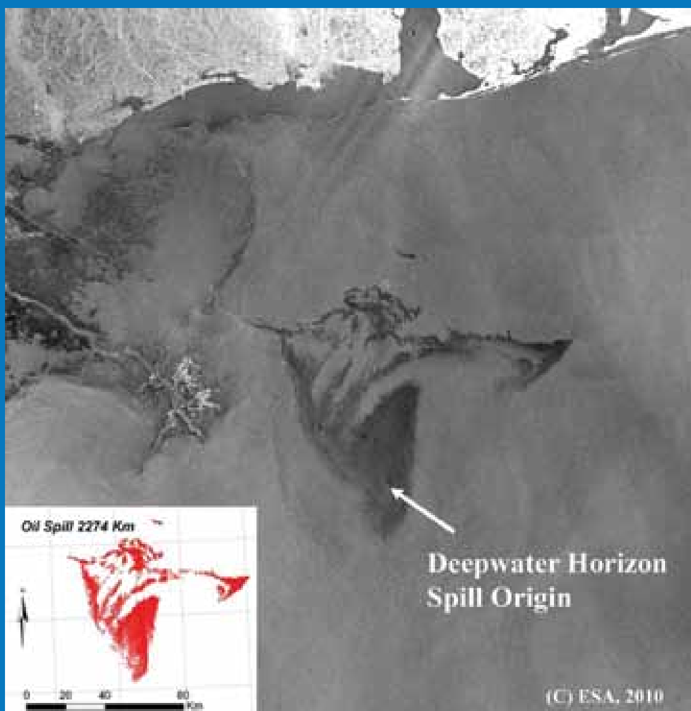
Synthetic Aperture Radar Images of Coastal Winds near Alaska



RADARSAT-1 SAR wind image, March 14, 2007 at 03:29 UT. The region shown is the Alaska coast of the Gulf of Alaska beginning at Kodiak Island at the bottom left of the image, and extending to Yakutat Bay at center right. Winds are from the north and northwest (indicated by arrows) with high winds extending southward over the ocean from gaps in the coastal mountains and islands. Wind arrows are from the Navy Operational Global Atmospheric Prediction System (same color bar as for the image). High winds can also be seen in the straits of Prince William Sound (center right of the image).

Deepwater Horizon - 2010

On 20 April 2010, the Deepwater Horizon oil rig exploded and sank, resulting in the largest oil spill in U.S. waters. Over the course of 4 months, more than 600 SAR data collections from 9 international satellites were used by STAR to determine the location and extent of the Deepwater Horizon slick in support of clean-up efforts.



The automated oil analysis shown in the inset was derived from this ENVISAT Advanced SAR (ASAR) image acquired 2 May 2010 at 3:51 UTC. The automated oil mapping algorithm is being developed in a collaboration between STAR and Florida State University. It is estimated that at this time the oil spill covered 2274 sq km.

Ocean Hazards Response: Oil spills

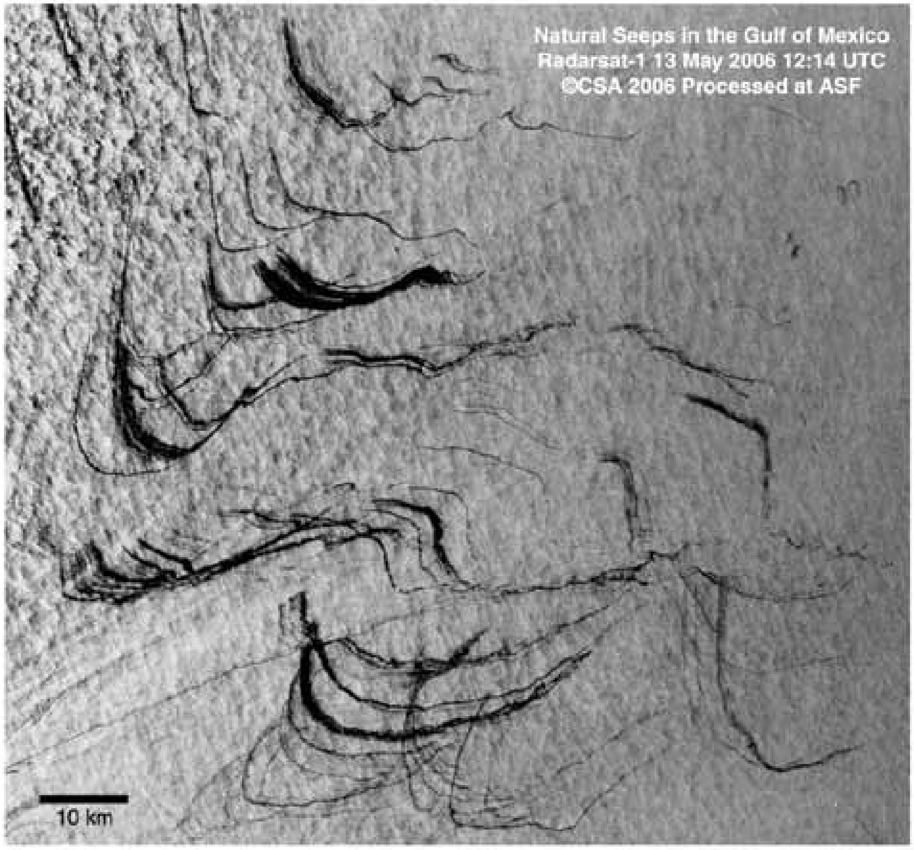
Christopher R. Jackson, William G. Pichel and Oscar Garcia-Pineda

Identifying and mapping the location and extent of oil on the ocean's surface is important for understanding and assessing its impact on the ocean and the coastal environment. Oil pollution can be the result of either natural seeps or accidental/intentional release during its extraction, use and transportation. Synthetic aperture radars measure the echo returns from many radar pulses as the satellite moves in its orbit, which are processed into a single radar image. It's a way of achieving very fine horizontal resolution without having to fly enormous radar antennas. Imagery from satellite-based synthetic aperture radar (SAR) is currently one of the best sources for detecting oil on the ocean's surface and can be used to effectively monitor large areas, with individual SAR images covering 100's of square kilometers.

The radar energy that is returned from the ocean is primarily from the short, wind-generated capillary waves. These are damped by surface oil, making the oil stand out by appearing darker than the ocean's surface under moderate wind conditions (3 - 12 meters/second). SAR also has the advantage of being able to make observations both day and night and to penetrate cloud cover. While SAR is sensitive to relatively small amounts of surface oil, care must be exercised so as not to confuse oil with other dark features such as low winds or upwelling water.

Currently, several countries use satellite SAR to support coastal monitoring for oil pollution from ship traffic. The satellite imagery is used to identify possible polluters, who can then be confirmed from aircraft or ship observations and subjected to heavy fines for illegal dumping. The imagery is also used to support hazard response during major oil spills, most recently the spill from the Deepwater Horizon event in the Gulf of Mexico. STAR scientists are currently working on advanced oil spill mapping algorithms, including multi-polarization methods.

Ocean Surface Oil Signatures in Synthetic Aperture Radar Images



Examples of ocean surface oil signatures. Left: Surface oil signatures resulting from natural oil seep leakage on the ocean floor are regular features in SAR imagery of the Gulf of Mexico. The slicks can extend for tens of kilometers and persist for several days. Right: Oil pollution from ships is a problem in coastal waters and is closely monitored in many parts of the world. Oil pumped from a ship's bilge leaves a characteristic trail behind the ship that is easily identifiable in satellite SAR imagery. The ship can be seen as the bright 'dot' at the end of the narrowing dark oil trail toward the upper right of the image.

Red, green and brown tides!

Harmful algal blooms (HABs) occur when certain species of algae grow quickly in the water, forming large patches. They come in a variety of colors – red, green, and brown. The blooms block the oxygen and sunlight that other organisms need to thrive, or emit toxins that are detrimental to humans and other life forms. It is estimated that HAB events cost the US coastal economy up to $82 million each year.

The NOAA CoastWatch program's ability to detect impending HABs through monitoring ocean color data is still one of its most popular uses. Ocean color data derived from satellites is processed into daily, average, and anomaly products that help scientists identify and track HABs. This information is then communicated to coastal managers and other agencies in the Gulf of Mexico – during the bloom "season" a special HAB bulletin is issued – to help them prepare for impending blooms. (Photo credit: NOAA Ocean Service)

CoastWatch

Kent Hughes and Michael Soracco

A harmful algal bloom is a rapid growth of algae, typically from nutrient rich waters, that impacts marine life or people by eutrophication (depletion of the oxygen in the water) or the production of toxic substances. In the late 1980s, a harmful algal bloom blanketed a section of the North Carolina coast and reportedly cost the community $25 million in damage and clean-up costs. In response to this event, STAR led the development of a NOAA program to collect satellite data to monitor the conditions of such blooms and give coastal managers advance warning of similar circumstances. Since then, this CoastWatch system has evolved into a robust collection of products that make near real-time oceanographic satellite data available to everyone.

Fast modern networks move data sets from receiving stations, through processing, to six regional nodes, and, ultimately, to the user. These regional nodes – operated through NOAA lines located in the U.S. East Coast (Chesapeake Bay), West Coast (Pacific Coast, California), Great Lakes (Ann Arbor, Michigan), Caribbean/Gulf of Mexico (Stennis Space Center, Mississippi), Alaska Region (Anchorage), and Central Pacific (Honolulu, Hawaii) – organize the data into a number of products, including ocean color, ocean surface wind, true color, and sea surface temperature from a variety of platforms and sensors. Custom products, such as those used to support the Deepwater Horizon Oil Spill event, are also provided using the expertise of personnel located at these regional offices.

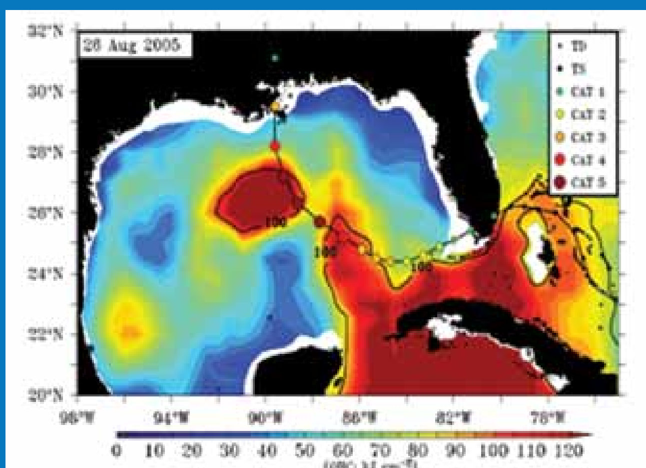
Modern technology has also made it much easier to adapt these data to a variety of systems. The CoastWatch Data Analysis Tool, for instance, is a graphic user interface program available from the CoastWatch website that enables users to handily manipulate satellite data for their unique applications. The CoastWatch team also continues to work on new and improved products, partnering with the European Space Agency and other international agencies operating satellite systems, to offer even more diverse and detailed data on ocean conditions across the globe.

The Deepwater Horizon Oil Spill

CoastWatch generates many products; this visible image is an example of the oil spill product used during Deep Water Horizon. The image, from the European Space Agency's Envisat MERIS (Medium Resolution Imaging Spectrometer) instrument, was provided by the NOAA CoastWatch Gulf of Mexico Node to the NESDIS Satellite Analysis Branch in support of NOAA's efforts to track the spill.

Katrina intensifies over warm Gulf waters

Hurricanes are fueled by warm ocean waters, which transfer a greater amount of moisture and heat energy into the atmosphere. As Hurricane Katrina moved across the Gulf of Mexico, it passed over pools of water with very high Oceanic Heat Content (red areas). As a result, It rapidly intensified to a Category-5 storm – winds greater than 155 mph – the highest level on the Saffir-Simpson Hurricane Scale. The illustration shows Katrina's track (black curve) and intensity (colored circles, red and dark red are category 4 (131-155 mph) and 5, respectively) overlaying a map of Ocean Heat Content derived from satellite radar altimetry.



Oceanic Heat Content

Eileen Maturi, Nick Shay and Jodi Brewster

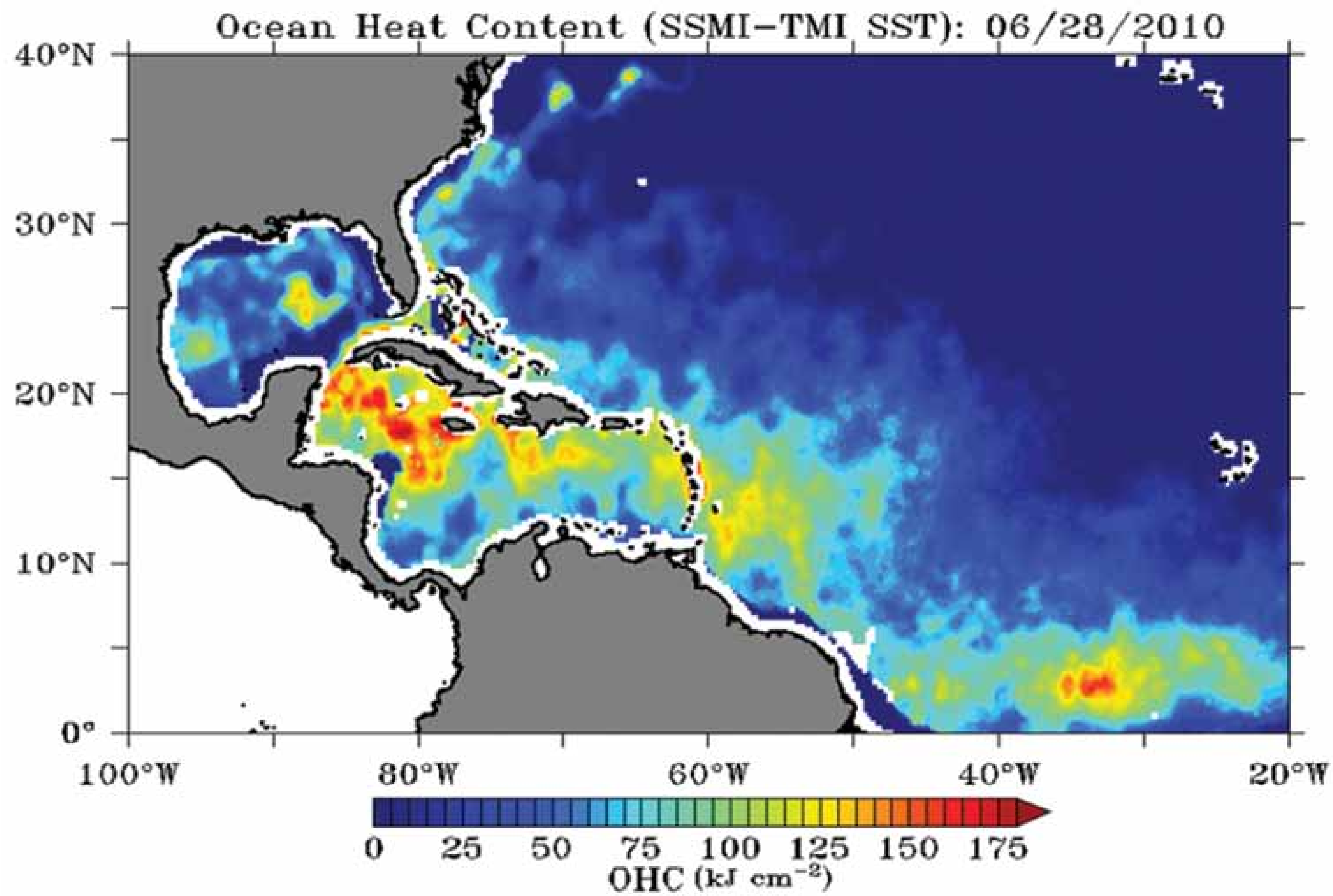
The passage of hurricanes over the ocean causes the sea surface temperature (SST) to drop (1 to 6 ˚C) in response to the strong winds that stir the upper layers of the ocean, bringing cooler waters from the lower depths to the ocean surface. The amount of cooling at the ocean surface depends on how quickly the hurricane moves over the ocean, the strength of the winds, and the depth of the mixed layer. The ocean mixed layer begins at the ocean surface and extends to depths of 25 - 100 meters.

The Oceanic Heat Content (OHC) is a measure of the heat contained in the mixed layer. The cooling effect of a hurricane is greatest when the mixed layer is shallow (25 to 30 m). If the layer is deep (≥ 50 m), the cooling influence is reduced because it is diffused over a larger layer. In this case, the OHC remains high, the SST decreases more slowly during hurricane passage, and the warmer ocean promotes storm intensification.

Global studies show that regions with high OHC are a better indicator of the ocean's effect on hurricane intensification than just the sea surface temperature alone. Satellite radar altimeters that measure the height of the ocean – sea level or the sea surface height – can be used to infer OHC variations, since as the ocean water warms it expands, and its level rises. OHC is being used at the National Hurricane and Joint Typhoon Warming Centers to forecast hurricane and typhoon intensities.

STAR scientists are generating an OHC product that combines satellite SST and altimeter measurements to obtain more accurate estimates of oceanic heat content (see figure, opposite page).

Oceanic Heat Content of the Atlantic Ocean Basin



Oceanic Heat Content (OHC) of the North Atlantic Ocean Basin on 25 June 2010 based on sea surface height measurements from three radar altimeters and sea surface temperatures from the joint NASA- Japan Aerospace Exploration Agency Tropical Rainfall Measuring Mission (TRMM) Microwave Imager. This satellite product is corroborated by temperature observations from the NOAA research aircraft.

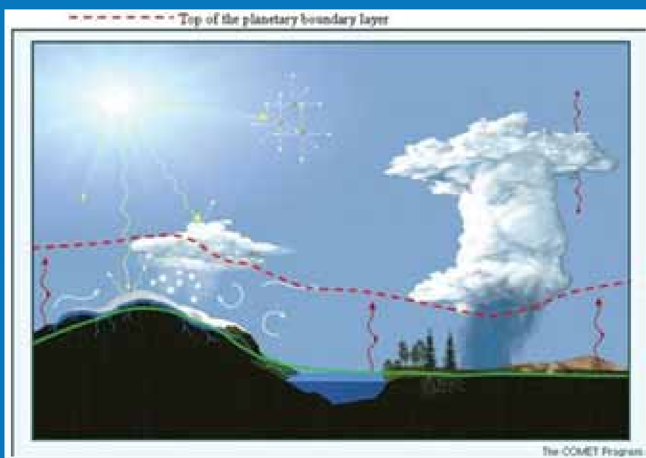
Section 5

The Land

Land-atmosphere interactions

The land surface is the lower boundary of the atmosphere. Along the land-atmosphere interface significant transfer of energy takes place by radiation, conduction, or convection. Evapotranspiration and precipitation are key processes in water exchange. Vegetation absorbs and emits various greenhouse gases through photosynthesis, respiration and decomposition. The land surface and any objects thereon also represent physical obstructions to the movement of air, resulting in friction or the diversion of airflow.

The proper representation of land-atmosphere interactions in numerical computer models is critical for weather and climate analysis and prediction. Satellite information on the land surface, such as vegetation cover, soil moisture, surface albedo (reflection of sunlight), or snow cover is provided at global or continental scales and is assimilated into advanced numerical weather prediction models.



Depiction of a continental surface and its interaction with the atmosphere. (Image credit: UCAR/NOAA COMET Program)

The Continents

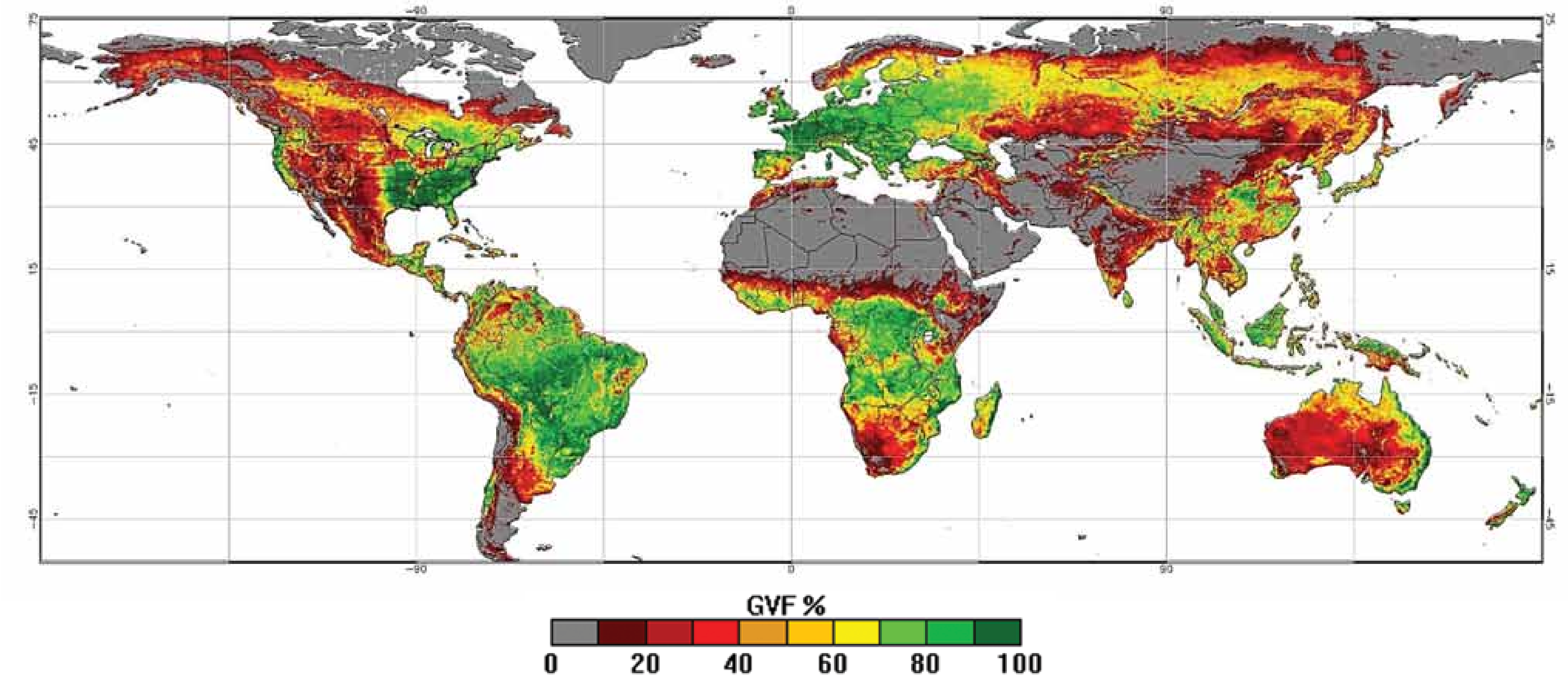
Ivan Csiszar

Land covers approximately one-third of the total surface of our planet. In its natural state, the vegetation, snow or ice cover of each location is determined by the climatic and geological conditions. Land also hosts a broad variety of animal species. Land, however, is also the primary habitat for mankind, and human activities have altered most of the habitable land area. Additionally, the land surface is an integral and critical component of the global climate system through its impact on radiation, water balance, and atmospheric and oceanic circulations.

Satellites are particularly suitable for the large-scale observation of land characteristics. Analysis of reflected solar radiation helps determine the amount and condition of vegetation. Sensors detecting infrared radiation are used to measure land surface temperature and detect fires. Microwaves penetrating deeper into the soil provide information on soil moisture content. Complex multispectral and spatial analysis is used to determine land cover type at an increasingly finer spatial scale. Disturbances, such as land clearing, insect infestation or fires can also be detected by satellites. In the chart on the next page, the Green Vegetation Fraction product shows areas where the amount of green vegetation is estimated from satellite measurements. This provides information about the state of the growing conditions in a region and also the surface background for use in NOAA's forecast models.

NOAA's environmental satellites have been extensively used for land surface monitoring. The Advanced Very High Resolution Radiometer (AVHRR) instrument on the NOAA polar satellites now provides a 30-year record or vegetation and fire activity. The GOES data are particularly useful for observing rapid changes, such as the diurnal cycle of land surface temperature. STAR scientists are developing a number of advanced land surface products for the next generation geostationary – GOES-R – and polar – Suomi NPP/JPSS – satellites.

Global Map of Green Vegetation Fraction

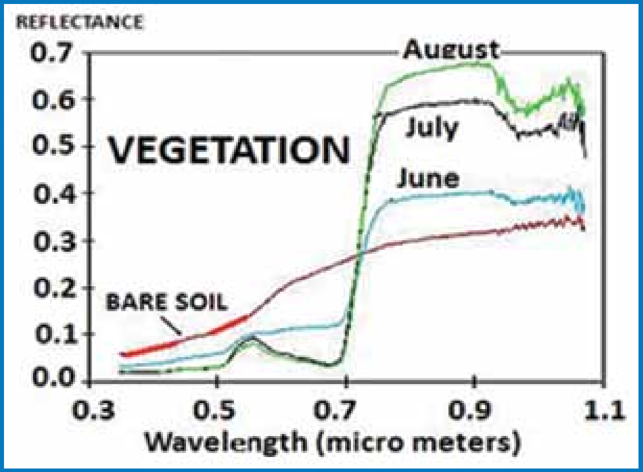


Global map of green vegetation fraction – the fraction of the surface covered with green vegetation – in May 2011. In this May snapshot of the annual cycle of vegetation activity, most vegetated areas in the mid-latitudes of the Northern Hemisphere already show vigorous vegetation cover; the green-up, however, is not yet widespread at higher Northern latitudes. Since May is a late spring month, many areas (like in the western U.S.) show a low fraction (red) of green vegetation since the mountainous terrain and cooler conditions delay the onset of greenup. In the southeast U.S., the spring conditions, typically with greater moisture and warmer temperatures, result in a higher green vegetation fraction.

Monitoring vegetation from space

Vegetation is green because the chlorophyll it contains absorbs the blue and red parts of the solar spectrum and reflects the green. This is the basis for the photosynthesis process, which converts the sun's energy to plant carbohydrate. With plenty of rain, sunlight, and warm temperatures, the forests, grasslands, and crops are green and abundant. But with prolonged adverse weather conditions, or with the reduced sunlight and colder temperatures in the fall and winter the amount of vegetation decreases and the vegetation color changes from green to yellow, brown, and red.

Being a strong absorber – or weak reflector – of the visible part (VIS, about 0.4 - 0.7 μm) of the solar spectrum, vegetation appears dark at these wavelengths (see diagram). But it strongly reflects near-infrared (NIR, 0.75 – 1.4 μm) radiation. Thus, the difference between the NIR and VIS is high for healthy vegetation and low for poor vegetation. This difference presents a basis for determining vegetation greenness and vigor from space.



Drought and Vegetation Health

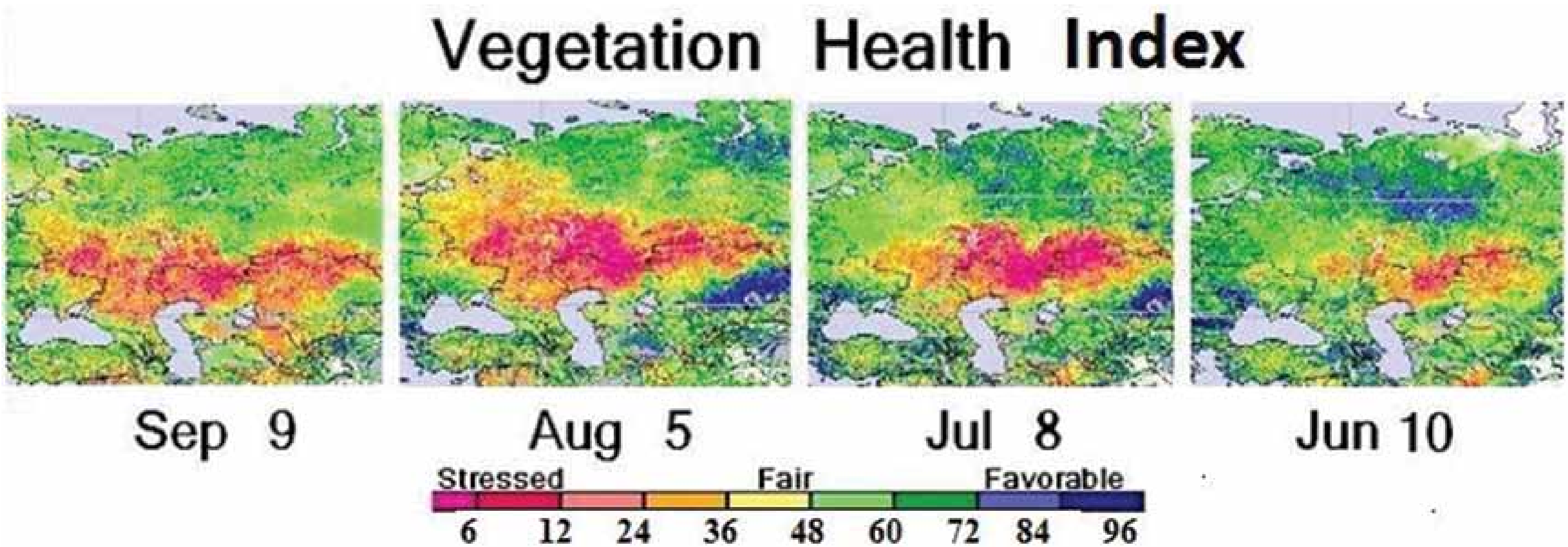
Felix Kogan

Drought is a typical phenomenon of the Earth's climate. The losses from droughts are staggering. In the USA, a country with advanced technology, the average annual cost of drought is around $6 billion. Weather station data used for drought monitoring are not sufficient because they characterize individual points rather than areas, and the observation network is limited and not uniformly distributed. Satellite systems offer an opportunity to overcome these difficulties.

STAR scientists have developed a vegetation health index (VHI) to characterize plant health based on measurements of the sunlight (VIS) and near infrared radiation (NIR) reflected, and the infrared radiation (IR) emitted, by the vegetation canopy. The reflected solar radiation observations serve as a proxy for vegetation greenness and vigor (see sidebar). The IR radiation is a measure of the vegetation's temperature. In dry years, the vegetation canopy overheats and loses vigor due to a lack of water. This intensifies the negative effects of the low moisture levels and slows vegetation development, reducing productivity. The combination of the solar reflectance and thermal emission measurements are a better indicator of vegetation health and drought intensity than either one alone.

The satellite-based VHI measurements are from the Advanced Very High Resolution Radiometer (AVHRR), which has flown on the NOAA polar-orbiting satellites since 1981. The reflected solar radiation observations are from the NIR and VIS channels, and the vegetation temperature measurements are from the 10.3-11.3 μm IR channel. The VHI varies from 0 (extreme vegetation stress) to 100 (favorable vegetation conditions), with 50 corresponding to average vegetation health conditions.

A Disastrous Drought in the Ukraine and Russia

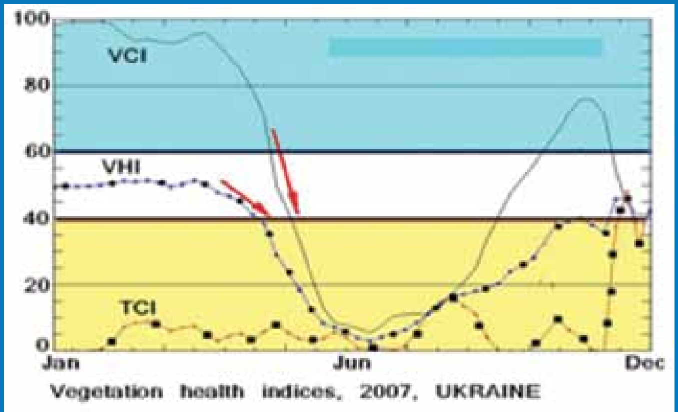


Monthly variations of vegetation health (a combination of moisture and thermal conditions) in Russia and Ukraine in 2010. Red indicates severe vegetation stress (<12). Vegetation stress began in the spring of 2010 and intensified through the summer and fall. The drought was exaggerated by thermal stress (not shown). The conditions were so severe that marsh areas of the north burst into flame and burned for two-three months until the fall's rains. The last time such severe conditions occurred was in 1972. With products such as the vegetation health index, the formation of a drought can be identified before it becomes severe, and this information can help guide planning for mitigating the effects of the drought.

Satellite indices for vegetation health and drought

Solar reflectance and infrared (IR) emission from vegetation canopies are converted to indices (proxies) characterizing vegetation greenness (Normalized Difference Vegetation Index, NDVI) and brightness temperature (BT), a measure of the vegetation temperature. NDVI and BT are converted to indices characterizing vegetation condition and health. These indices are Vegetation Condition (VCI, based on NDVI), Temperature Condition (TCI, based on BT) and Vegetation Health (VHI, based on a combination of VCI and TCI).

The image shows VCI, TCI and VHI dynamics during the 2007 severe drought in the Ukraine. The area of vegetation stress (intensifying towards zero) is yellow and favorable conditions are blue. The 2007 drought was triggered by extreme thermal stress (TCI), which aggravated the moisture condition (VCI) and vegetation health (VHI) in the summer.



Global Vegetation and Society

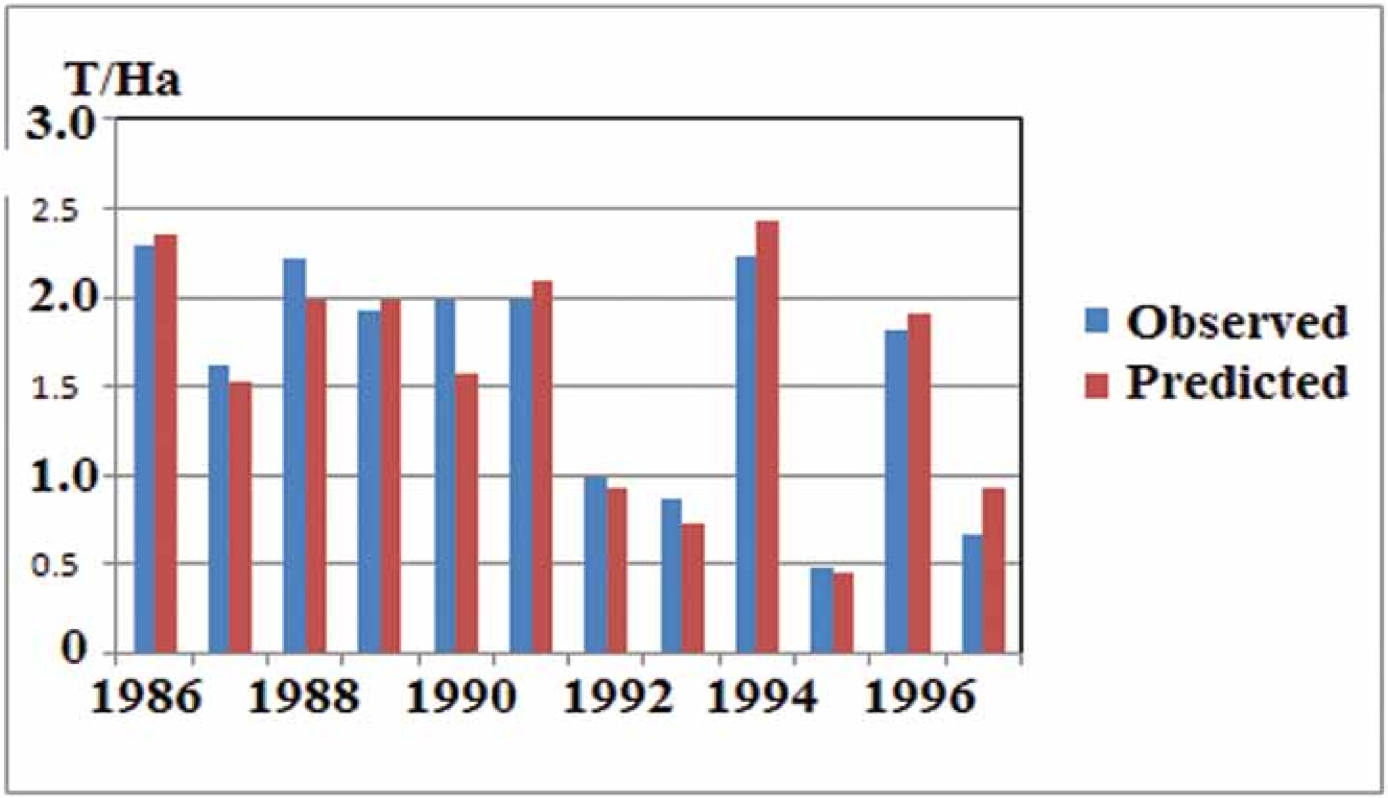
Felix Kogan

Global vegetation health depends on weather, climate, and ecological processes, as well as human activities. Changes in vegetation health, in turn, feedback on, or affect, many aspects of the environment. STAR has constructed a global vegetation health (GVH) data set for operational monitoring, assessment, and prediction of a wide variety of environmental conditions. The data set is global, available since 1981, and has a spatial resolution of 4 km. It contains measurements of sunlight reflected from, and infrared (IR) radiation emitted by, the vegetation; indices of vegetation condition, temperature condition, and vegetation health constructed from the reflectance/emission measurements; climatological values of the data; and other products.

The GVH data and products address the following issues:

- Prediction of crop and pasture production
- Estimation of fire risk area and intensity
- Monitoring mosquito-borne diseases
- Early drought detection and monitoring its area, intensity, origination and impacts
- Flooded and saturated soil
- Climate change and vegetation trends
- El Niño/La Niña impacts on land cover
- Relationships between ocean temperatures and ecosystems
- Global warming and regional climate change
- Environmental security (air and soil pollution)
- Vegetation coverage and ecosystem characterization for NWP models
- Monitoring invasive species
- Land cover change
- Food security
- Climate constraints, technology and grain production

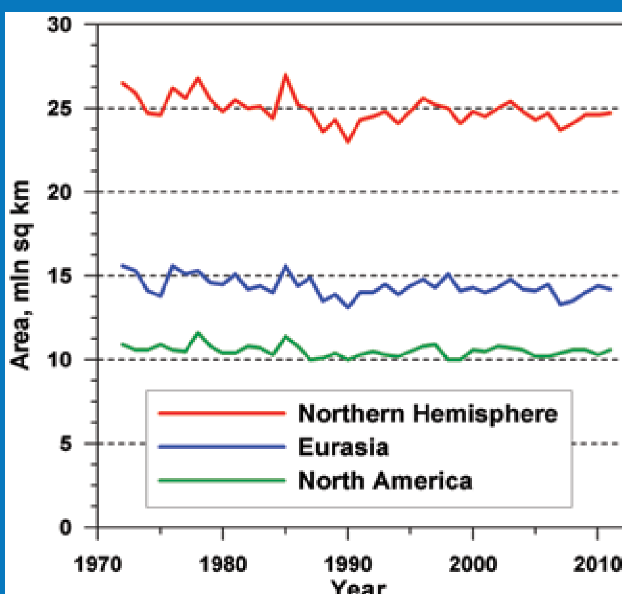
Predicting Agricultural Output



Comparison of agricultural output (crop yield, tons/hectare) predicted from Vegetation Health (VHI) data and observed output in Morocco. The prediction model is based on statistical relationships established between the VHI and measured future agricultural output. The predictions correctly forecast most of the variations in agricultural output.

Is the area of the Earth covered by snow changing?

Estimates of the yearly average snow extent derived from NOAA's satellite-based snow cover maps show an overall decreasing trend both in Eurasia and North America (see the figure), and thus are generally consistent with other indications of global climate warming. But most of the decrease occurred in late 1970s and 1980s, and there has been no clear change in snow extent in the 1990s and 2000s. A possible explanation is the increasing number of heavy snowfalls in mid-latitudes in the 1990s and 2000s, which may be related to circulation changes associated with global warming. Climate modeling studies provide some support for this hypothesis.



Yearly average snow-covered area

Snow Cover

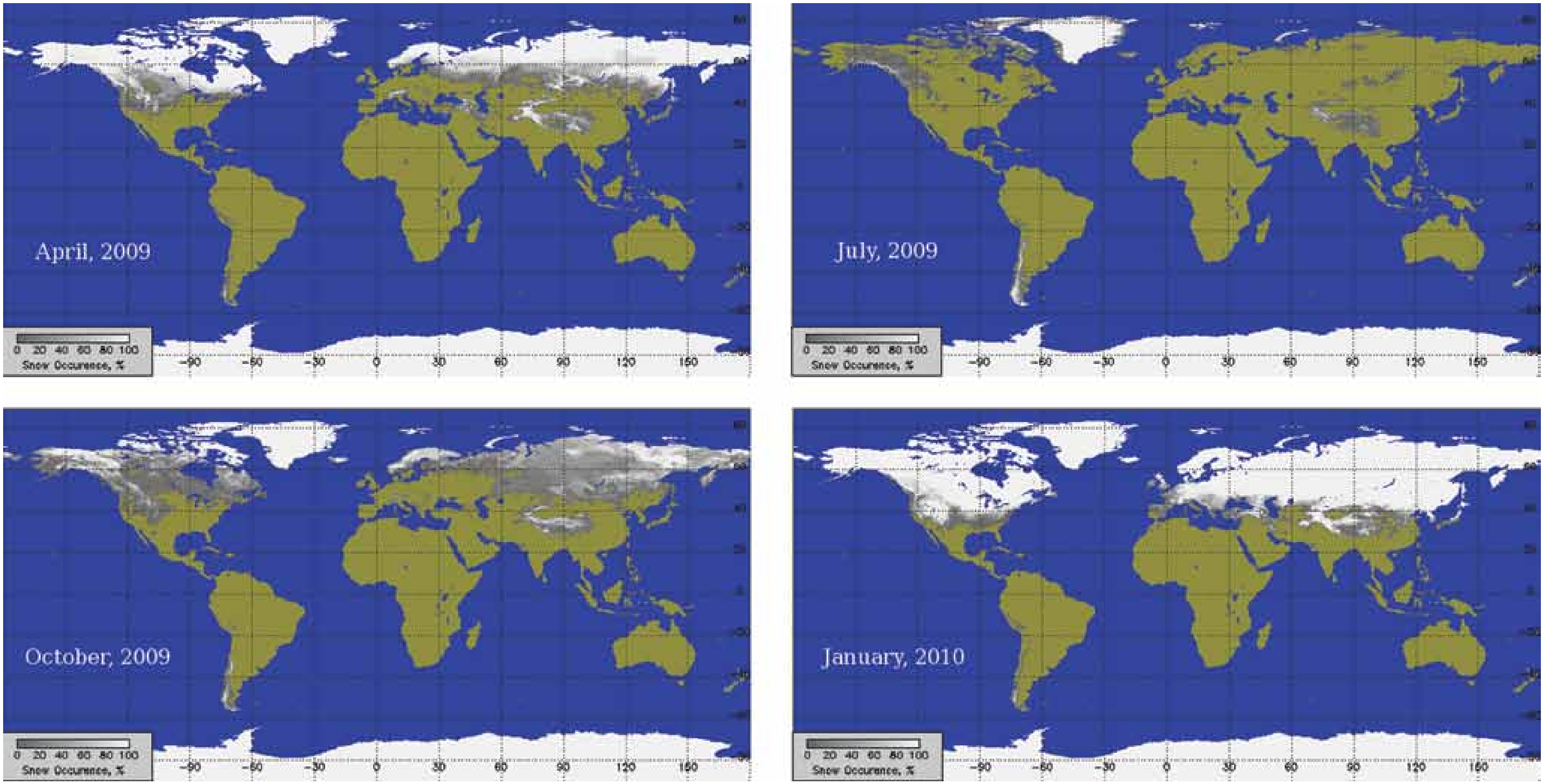
Peter Romanov

About one third of the Earth's land surface is affected by seasonal or perennial snow cover. Accurate and timely information on the areas covered by snow, its depth, and its physical properties is important for weather prediction, transportation, electric power generation, water management, recreation, and a number of other practical applications. In many areas of the world, humans rely on seasonal snow and glaciers as the major source of fresh water for drinking and agriculture. Snow cover is also a sensitive climate change indicator: shorter snow cover duration in winter and earlier snow melt in spring are among the most obvious consequences of the general warming of the Earth's climate.

Satellites have been used to monitor the extent of global snow since the late 1960s. The first snow mapping technique implemented at NOAA involved human analysts who visually examined satellite visible images and drew maps of snow cover by hand. This technique has proved to be robust, reliable and accurate and therefore, despite its high labor cost and lengthy production time, still remains operational at NOAA. Since the mid-1970s automated satellite image classification and snow mapping programs have been widely used. Automated techniques utilize observations made with satellite sensors in the visible, thermal and microwave spectral range.

STAR scientists are working on the development of advanced automated snow detection and mapping algorithms. These algorithms combine observations made in different spectral bands from both polar orbiting and geostationary satellites. With current satellite systems, information on the snow cover distribution over the entire globe can be updated one-two times a day at a spatial resolution of several kilometers.

Annual Cycle of Snow Cover



Global maps of snow cover frequency of occurrence for the months of April, July, and October 2009 and January 2010. The monthly maps are based on corresponding NESDIS daily snow maps derived with an automated algorithm from combined observations of polar orbiting and geostationary satellites. White color indicates locations with persistent snow during the entire month, dark gray shows areas where snow cover was intermittent or was observed only several days during the month.

How soil moisture of the land surface may affect your daily life

Most people know that dry soil may kill crops in the fields and grass in their front yards. They may also be aware that very wet soils result in muddy roads, hampering land transportation and, for example, an army's ability to move its mechanized forces. But they probably do not know that large scale soil moisture has significant impacts on weather and climate forecast accuracy, the world crop commodities markets, the likelihood of flash floods, the management of agricultural and city water, and the spread of vector borne diseases such as Dengue fever and malaria.

In Spring 2010, a severe drought devastated a vast region of southwest China. By March 2, 2010, more than 4 million hectares of crops were damaged, and 15 million people and 9 million livestock had lost access to fresh water. If continuous soil moisture monitoring had been in place, early warnings could have been issued, and better drought mitigation plans prepared and implemented.

A Chinese farmer walks across a dried-up reservoir in Shuitang village in southwest China during the drought of 2010. (Photo credit: AP)

Soil Moisture

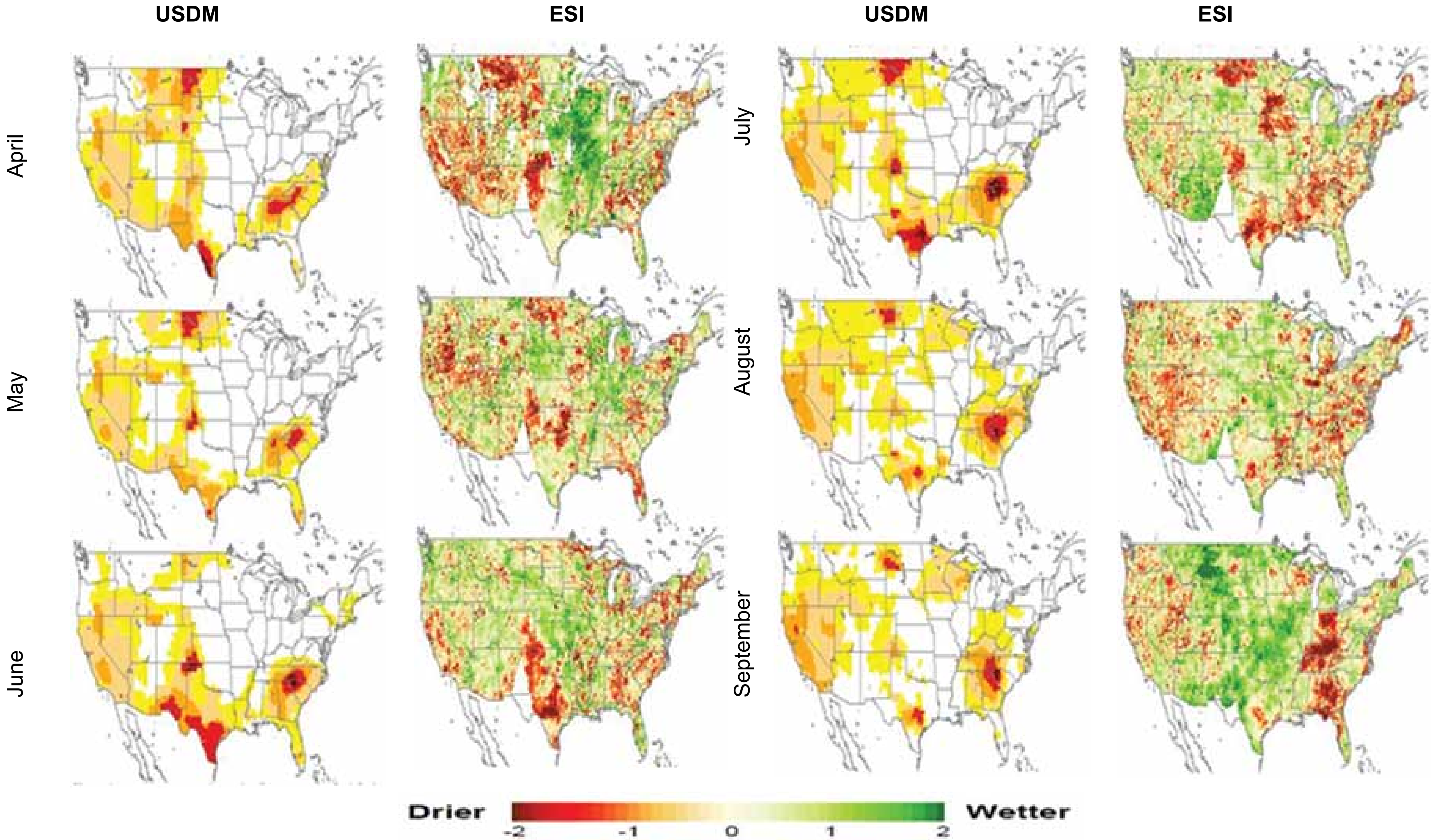
Xiwu Zhan, Jicheng Liu, Christopher Hain and Martha Anderson (USDA)

Soil moisture is the amount of water in the soil – the top-most stratum of the Earth containing the roots of plants, crops, and trees. The ability of the soil to emit low-frequency microwave radiation depends on its dielectric constant, which in turn is controlled by its water content. Thus, microwave radiation emitted by the land surface and observed by a satellite sensor is related to soil moisture amount. Researchers at STAR are developing a global Soil Moisture Product System (SMOPS) using microwave satellite sensors. Currently the Advanced Microwave Scanning Radiometer on the NASA Earth Observing Satellite Aqua, the Advanced Scatterometer on the Metop satellite of the European Organization for the Exploitation of Meteorological Satellites, and the Soil Moisture Ocean Salinity satellite of the European Space Agency provide observations that help characterize the soil moisture. The Soil Moisture Active/Passive mission of NASA, to be launched in 2014, is specifically designed to monitor global soil moisture.

Land surface temperature – in particular the rate of change of temperature during the day – depends on soil moisture content, through its control of the soil's heat capacity and evaporative cooling. STAR scientists and U.S. Department of Agriculture (USDA) collaborators are developing a new technique to generate soil moisture information from the surface temperature measurements of the thermal infrared sensors on the GOES satellites (see opposite page).

Satellite soil moisture data products are being used in the multi-agency U.S. Drought Monitor, in NOAA's numerical weather and seasonal climate prediction models, and in world crop forecasts of the USDA's Foreign Agricultural Service.

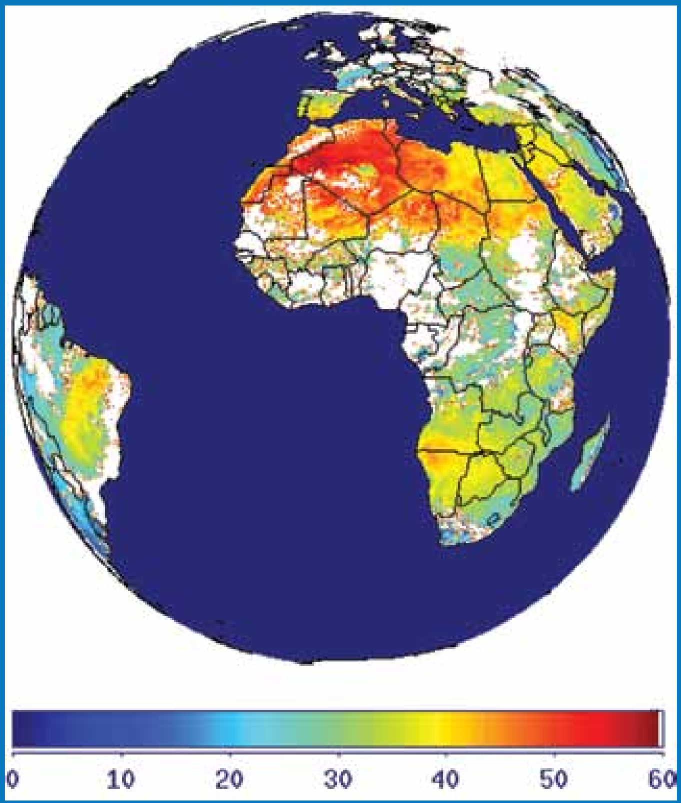
Monitoring Droughts with Satellite Soil Moisture Measurements



Maps of Evaporative Stress Index (ESI) – a measure of soil moisture from a model using GOES IR observations – compared with the Monthly US Drought Monitor (USDM) for the growing season of 2008. The GOES-based maps match the USDM maps well and have higher spatial resolution. The ESI is being tested for operational applications, for example, to supplement model estimates and microwave observations as input to the U.S. Drought Monitor.

Land temperature: The view from space

A land surface temperature map for Aug 30, 2007, 14:15 GMT is shown below. Observations are from the European Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI). Blue and white colors indicate ocean and cloud areas, respectively. The color bar scale shows the temperature in degrees Centigrade. The hot Saharan Desert areas – close to 60 °C or 140 °F – are clearly seen.



Land Surface Temperature

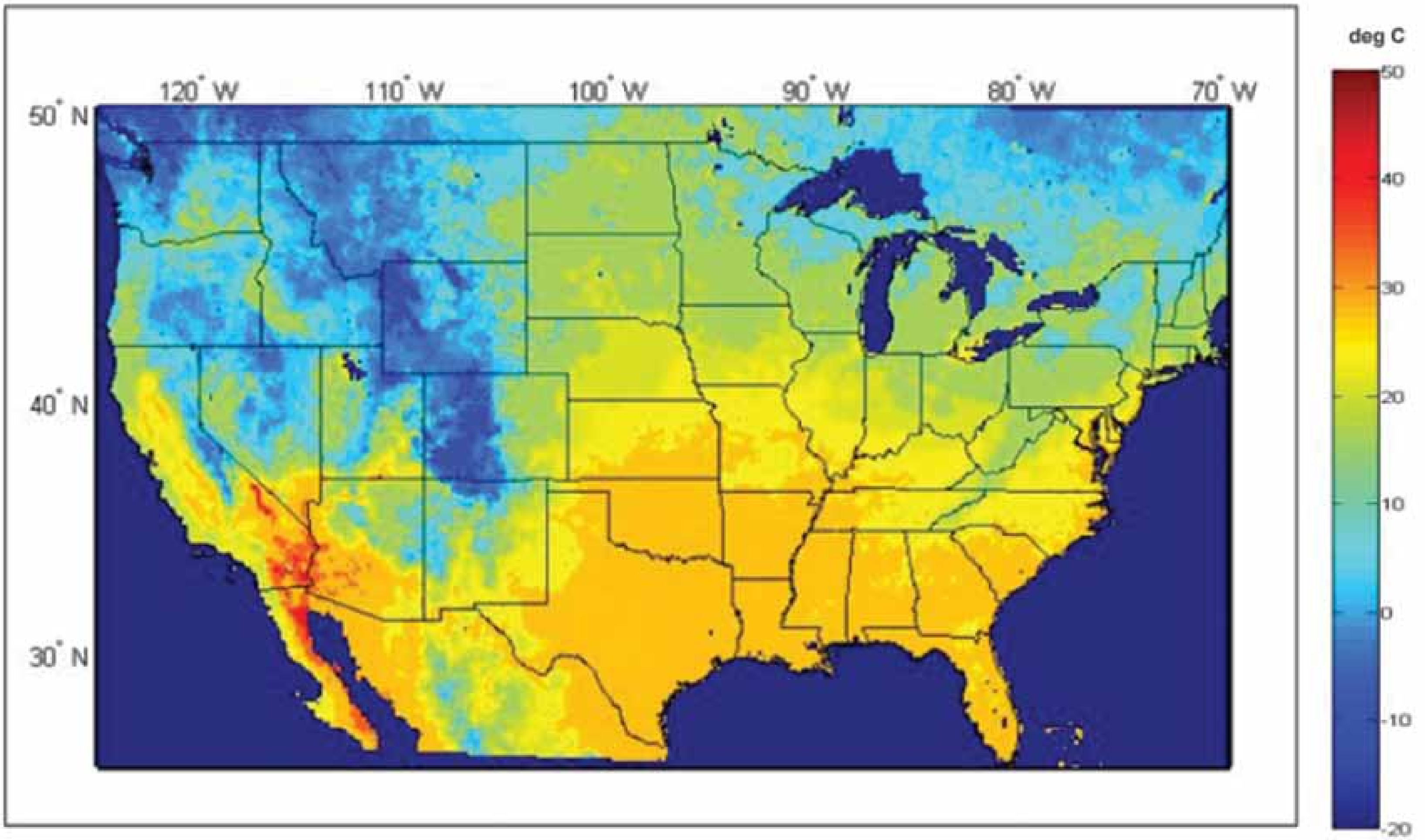
Yunyue Yu, Yuling Liu, and Xiaolong Wang

Most of the solar energy incident on the Earth is absorbed at the surface. This absorbed energy drives our weather and climate. The Land Surface Temperature (LST) is a key indicator of the fraction of the absorbed energy used to evaporate surface water or to heat the air near the surface. It is fundamental for estimating the net radiation budget at the Earth's surface and for monitoring the state of crops and vegetation. Long term trends of LST are indicative of the rate of greenhouse warming. Satellite land surface temperatures have been routinely available from geostationary and polar-orbiting satellites. As of 2011, more than 30 years of global satellite LST had been accumulated.

Land surface temperature is determined from the measurements of infrared (IR) radiation in an atmospheric 'window' (a portion of the electromagnetic spectrum where atmospheric absorption is a minimum) under clear sky conditions (since clouds absorb the IR radiation). Corrections are made for the small amount of atmospheric absorption that does occur.

Satellite LST is assimilated into NWP models, climate models, and mesoscale atmospheric and land surface models to estimate the exchange of energy between the surface and atmosphere by radiation, evaporation, conduction, and convection. Commercial applications include the use of LST to evaluate water requirements for crops in summer and estimate where and when damaging frost may occur in winter. High LST is a warning sign for possible forest and grass fires, as well as an indicator of possible drought.

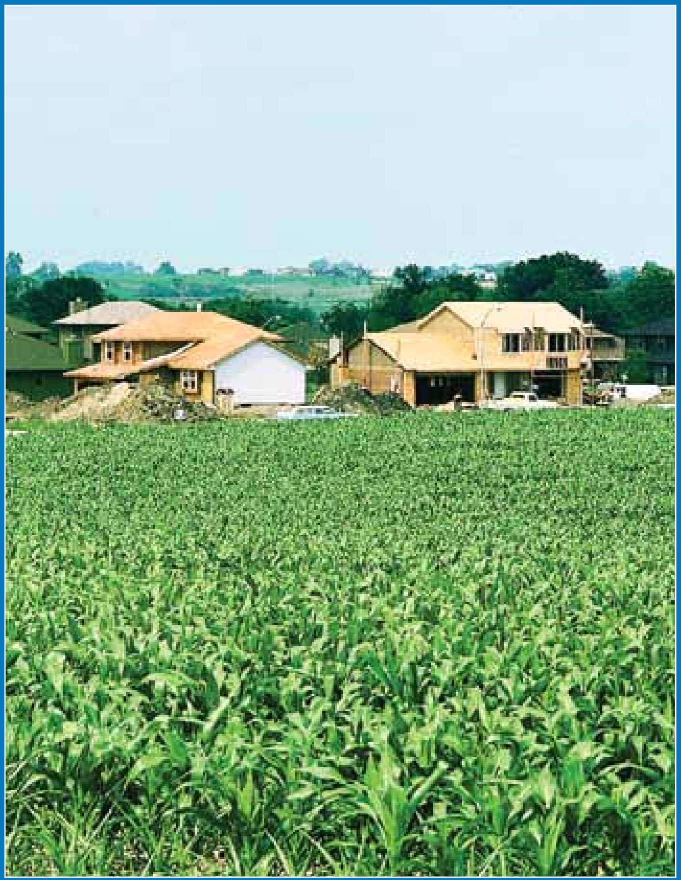
Continental U.S. Land Surface Temperatures for the Month of July



A map of mean land surface temperatures for the month of July compiled from GOES satellite observations. The temperatures in July tend to be high, and in the southern U.S. range from 20 to 30 degrees Celsius, or approximately 68 to 86 degrees Fahrenheit. The temperatures are lower in the Rocky Mountains due to their higher elevation and are also less uniform there due to the complexity of the terrain.

From farms to cities

Urban population within the United States initially surpassed the rural population in 1920, and the portion of U.S. population within urban areas has increased steadily to greater than 80% in 2010.



Example of the expansion of urban areas into rural areas. (Photo credit: US Department of Agriculture)

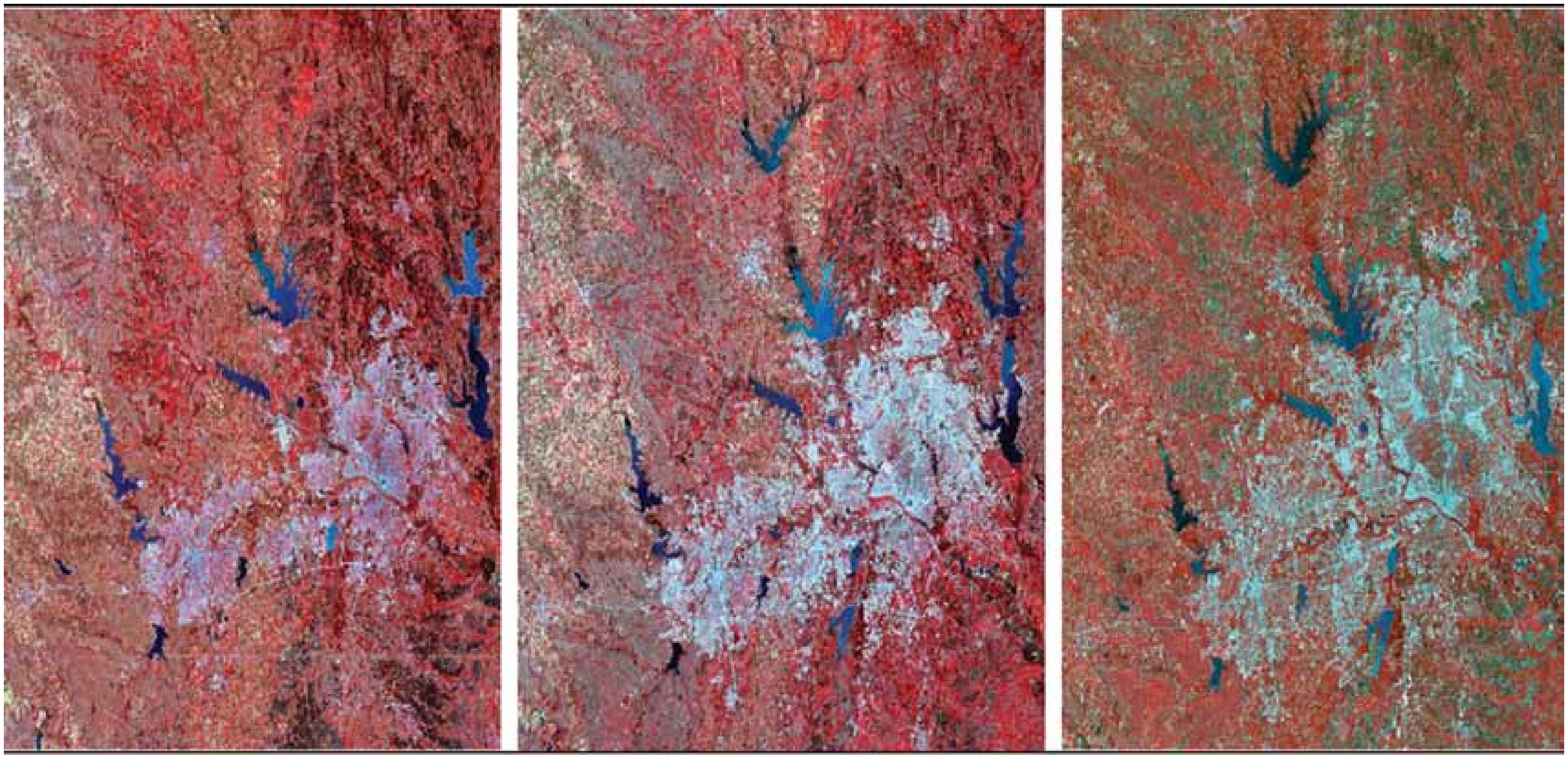
Urbanization, Heat Islands, and Climate

Kevin Gallo

American cities are growing, and are projected to continue to expand as rural migration to urban areas continues. Urban population within the United States initially surpassed the rural population in 1920, and the portion of U.S. population within urban areas has increased steadily to 81% in 2010. The influence of urbanization on local and regional climate (often called the Urban Heat Island Effect) has been well documented. Urban areas tend to have higher nighttime temperatures and a smaller daily difference between maximum and minimum temperatures, compared to nearby rural areas. Urban development influences local climate through a wide variety of processes that result from the conversion of natural land cover (often some type of vegetation) to developed land (rooftops, asphalt, and concrete). In addition to differences in temperatures between urban and rural environments, indirect observations of the influence of the urbanization (e.g., length of growing season), have also been observed. Health-related concerns within urban environments during the summer months frequently result in weather warnings associated with elevated temperatures and decreased air quality.

STAR investigators are using satellite data to observe and monitor the differences in the physical features of urban and rural environments that contribute to the Heat Island Effect. Satellite observations of land surface temperature and green vegetation have been used to estimate differences in air temperatures that might be due to increased urbanization. These monitoring efforts are also critical to assure that changes in land use and urbanization do not interfere with measurements of global climate change.

Growth of Dallas/Fort Worth over Three Decades



Landsat images from 1974 (left), 1989 (center) and 2003 (right) show vegetation in red, water in blue, and urban areas in white or grey tones. Similar images and data can be used to determine the influence of the city area on the local climate, and changes that may affect humans, plants, and insects within the urbanized regions. (Landsat images courtesy of US Geological Survey)

Deforestation and fires in the Amazon

Deforestation in the Amazon is occurring primarily to clear land for agricultural use. The live vegetation removed from the rain forest is piled up until it is dry enough to burn. During the dry season, thousands of such fires are set throughout the region. Satellites detect many of these fires and the information provided helps land management and other government agencies to monitor, regulate and enforce the controlled use of fires.

The Amazon is observed at favorable near-nadir view angles with NOAA's geostationary (GOES East and West) satellites. An operational fire product, using the Wildfire Automated Biomass Burning Algorithm developed by STAR, has been generated since 2002. It is used extensively to study fire occurrence in the region.

Aerial photograph of burning agricultural wastes in the Amazon. Many such fires are detected by the GOES satellite. (Photo credit: NASA)

Vegetation Fires

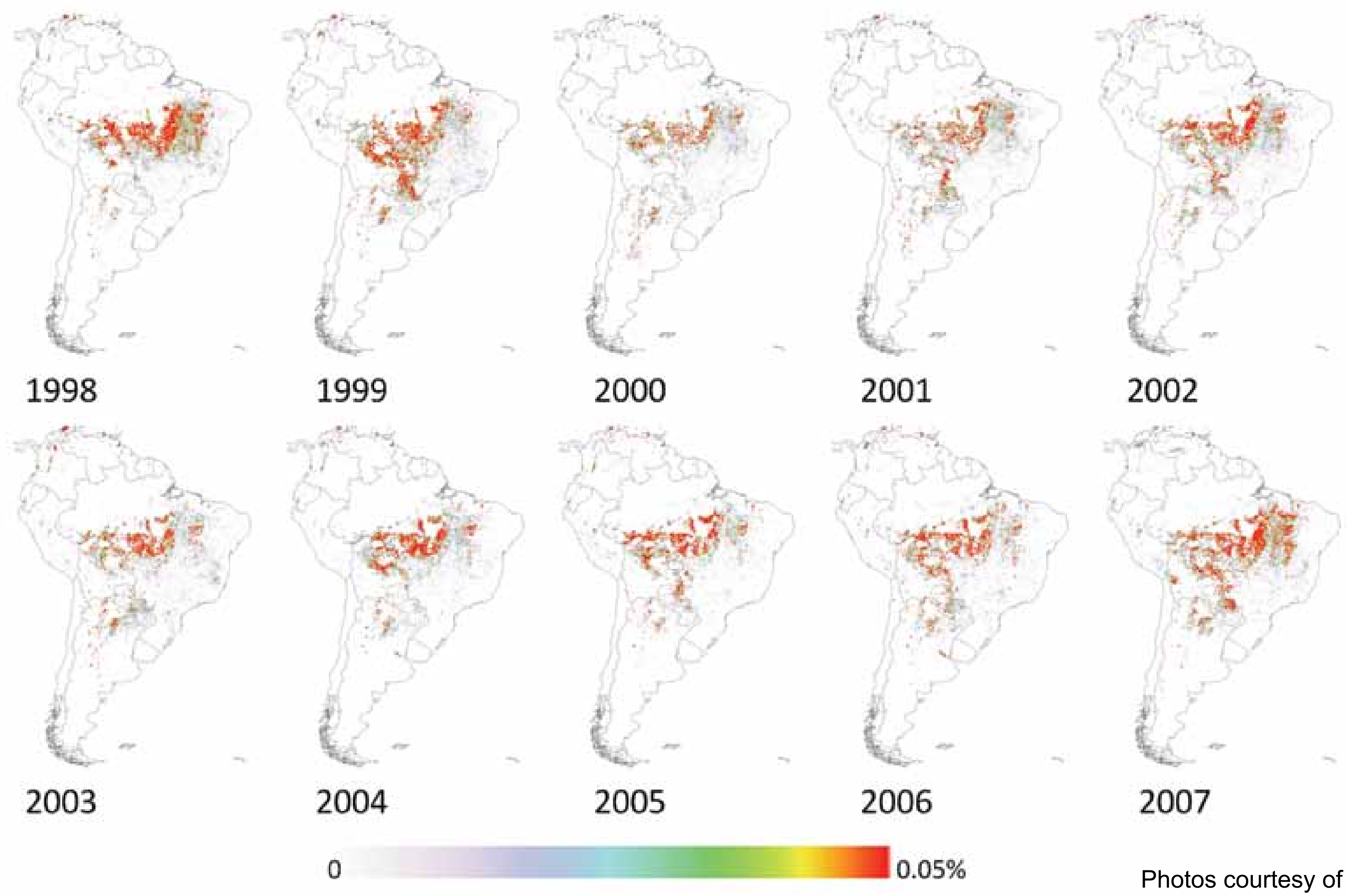
Ivan Csiszar, Christopher Schmidt, and Wilfrid Schroeder

The burning of forest or other vegetation cover (also called biomass burning) is a process of paramount importance for our planet and for our society. Emissions of gases and particulate matter from fire affect atmospheric composition, weather and climate. Burning of vegetation cover can also permanently alter the landscape. Fire is one of the major natural disasters that can severely impact human life and property. Smoke emissions from fires represent a major health hazard and also impact transportation safety. Fires set by humans are used in agricultural land management, including slash-and-burn agriculture, which is a major agent of deforestation.

Fires are found across a wide range of ecosystems around the world, including remote and unpopulated areas. Accurate and consistent large-scale fire monitoring is possible only using Earth observing satellites. Sensors that include measurements in the near infrared (4 μm) are particularly useful; the radiative emission spectrum of high temperature fires peaks at this wavelength making it particularly sensitive to detecting fires. NOAA's GOES satellite series provides observations at high temporal frequency, thus enabling the mapping of diurnal fire activity over the Western Hemisphere. Sensors on polar platforms, such as NOAA's POES or NASA's EOS Terra and Aqua satellites, with their finer spatial resolution (≤ 1 km) detect smaller fires, but only a few times a day.

Changes in global fire regimes, in particular the frequency and distribution of wildfires, have been linked to climate oscillations (e.g., El Niño) and to land management (e.g., fire suppression and forest conversion). The long-term archive of satellite data now enables reconstructing and analyzing fire history since the mid-1990s.

Ten Years of Fires in South America



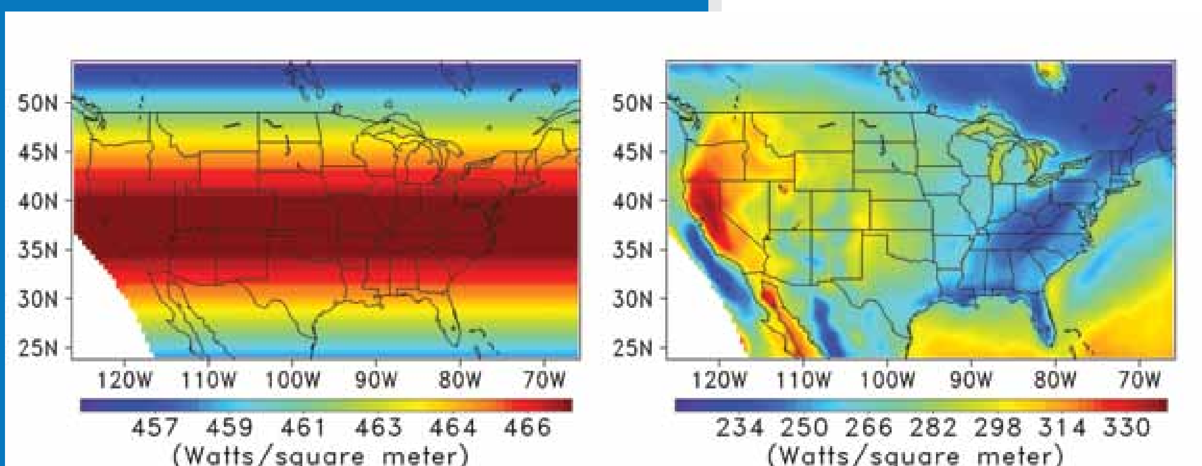
Photos courtesy of UMD and CIMSS

The fraction of observations with fires detected from the GOES-East satellite. Data show only detections in July, August and September, which is the peak dry season and the time of high fire activity in the tropical regions of South America south of the Equator. Most of the activity is concentrated along the Arc of Deforestation, where the Amazon rain forest has been cleared by slash-and-burn agriculture. Other fires can be attributed to annual agricultural maintenance. Note the variation between years due to climate conditions and varying human activity.

The journey of sunlight though the atmosphere

As sunlight enters the Earth's atmosphere and travels to the surface it encounters clouds, gas molecules and aerosols. As a result of these encounters, about 30% of the sunlight, on average, is reflected back to space and is not available to heat the Earth. 20% is absorbed in the atmosphere and 50% is absorbed by the land and ocean surface. The absorbed energy is converted mostly to heat that warms the surface and the atmosphere.

Computer models – solutions of radiative transfer equations – that specifically account for the interactions between light, the surface and the atmosphere are used in estimating the sunlight available at the surface. The example below shows how the regular and symmetric pattern of light on an average July day over the continental U.S. before entering the atmosphere (left panel) is changed by these interactions by the time it reaches the surface (right panel.)



Sunlight

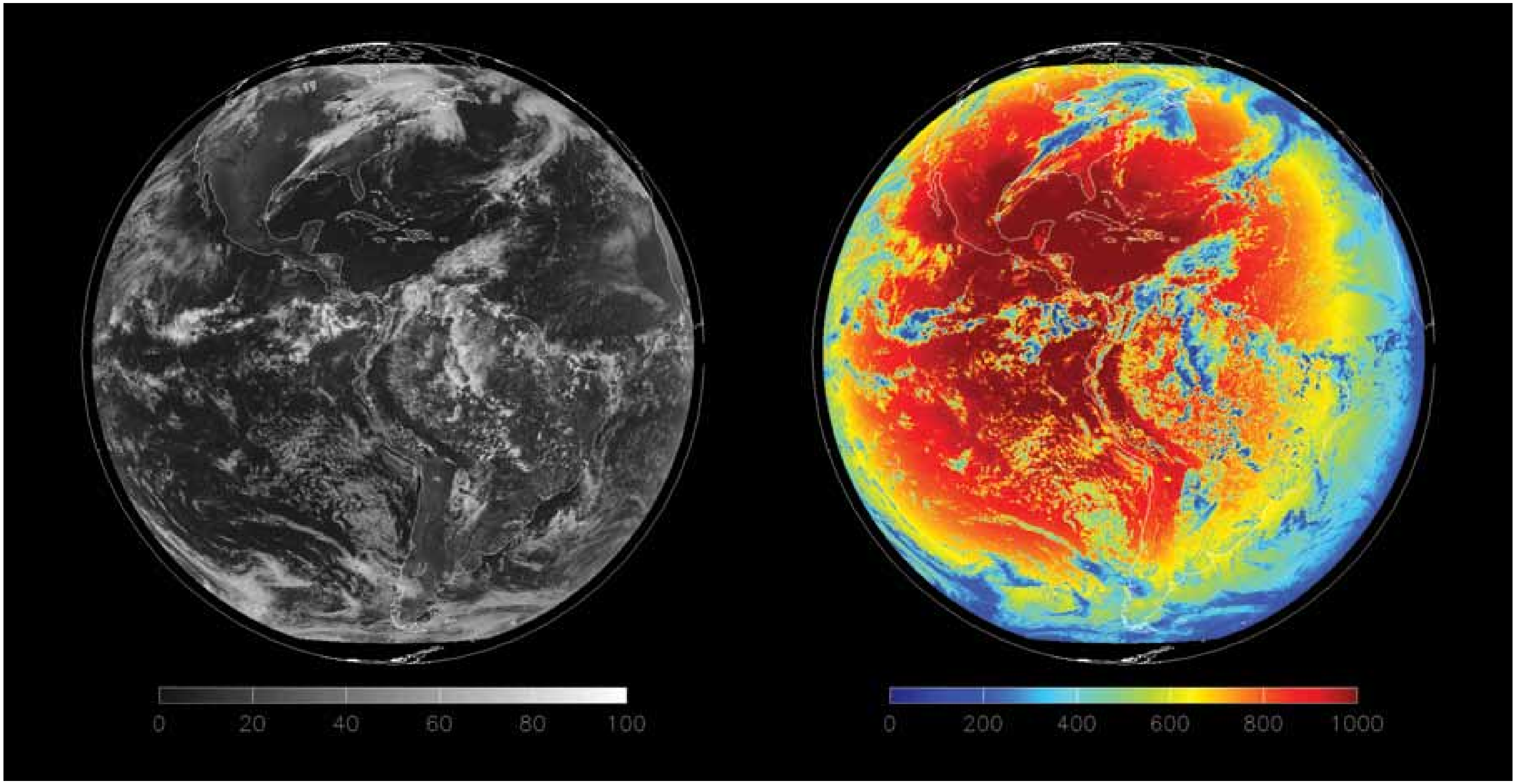
Istvan Laszlo

Sunlight is the term used to collectively describe the light from the Sun with different colors. 99% of all colors in sunlight are represented by the familiar rainbow colors of visible light and the colors of ultraviolet and near infrared light that are invisible to the human eye. Sunlight delivers energy from the Sun to the Earth, where it warms the surface and the atmosphere, drives weather and climate and determines processes that are vital for life. Part of this energy is captured in solar power plants and converted into electricity.

The amount of sunlight reaching the Earth's surface (also called solar radiation or insolation) varies according to geographic location, season, time of day, and local weather. STAR scientists use sophisticated computer models to calculate the amount of sunlight available at the surface from measurements made by satellites. This is possible because the amount of sunlight striking the uppermost layers of the atmosphere is well known, and the fraction of energy that makes it through the atmosphere can be calculated from the reflected sunlight (from clouds and snow/ice mainly) observed by satellites. Polar orbiting satellites enable global observations of sunlight at the surface, including remote oceanic and land areas where conventional ground measurements are not readily available. Measurements from geostationary satellites allow the calculation of sunlight at different times of the day. This is very important for many applications (e.g. solar power, prediction of coral bleaching) since changing meteorological conditions (cloudiness) significantly alter the amount of sunlight available at the surface.

The sunlight derived from satellites is used in the verification of forecasts from numerical weather prediction models. It is also one of the key inputs to models that predict coral bleaching.

From Satellite Image to Sunlight



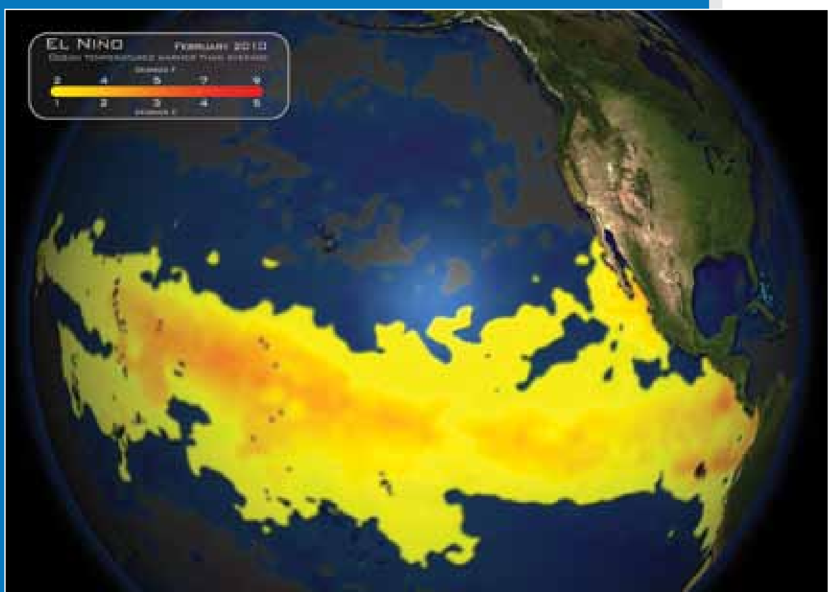
The computer model developed at STAR converts the visible image taken by the satellite instrument (left) into an estimate of sunlight at the surface (right). White areas in the satellite image represent bright, thick clouds while dark gray areas are mostly free of clouds. The white cloudy areas in the satellite image are translated into low sunlight (shades of blue) while the dark cloud-free areas are translated into high sunlight (red to dark red colors). Note that the range of sunlight varies significantly (between zero and 1000 Watts/square meter) depending on cloudiness and the height of the sun above the local horizon. (The example shown uses the image taken by the imager instrument onboard the Geostationary Operational Environmental Satellite (GOES) 13 on April 11, 2011 at 17:45 UTC.)

Section 6

Climate

Blame it on El Niño

In 1997 Halloween celebrants sported a record number of "El Niño" costumes, a sign of both the record high ocean temperatures off the coast of Peru and of the incredible media frenzy that resulted. Advanced satellite and in-situ observations at the time clearly showed the strong El Niño conditions (the temperature in the Pacific equatorial region was much warmer than average as shown in the figure below in the yellow to orange colors) and this meant winter was likely to be warmer than normal in the northwest United States, and wetter than usual in the southeast. However, to many in the general public the message became muddled, and nearly every bad weather event was blamed on El Niño, making it a great idea for a scary costume.



Warmer than normal Equatorial ocean temperatures indicative of El Niño.

Our Changing Planet

Ingrid Guch

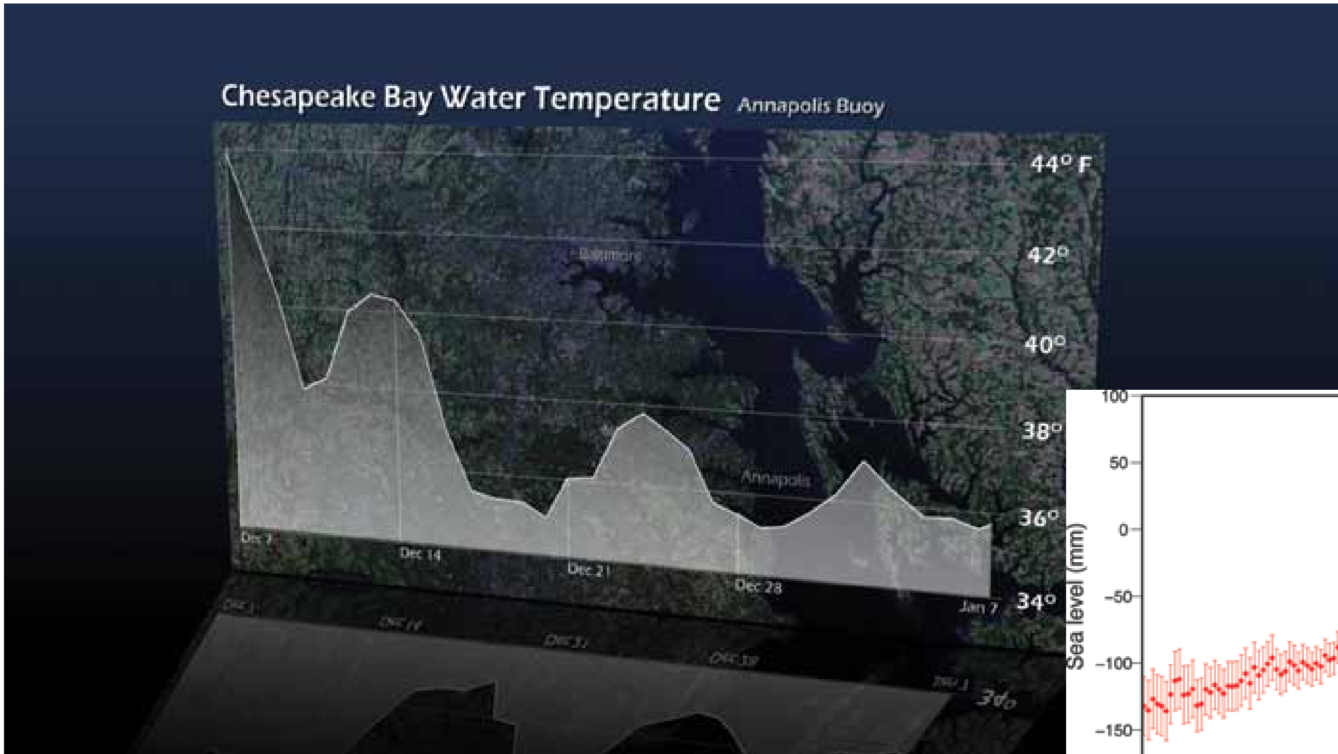
What is climate and why is it important? Climate reflects the most likely or expected weather based on long term observations of actual weather conditions accumulated for a given time period and location. Useful climate information includes averages for a date and time, as well as information about the likelihood and size of deviations from the average.

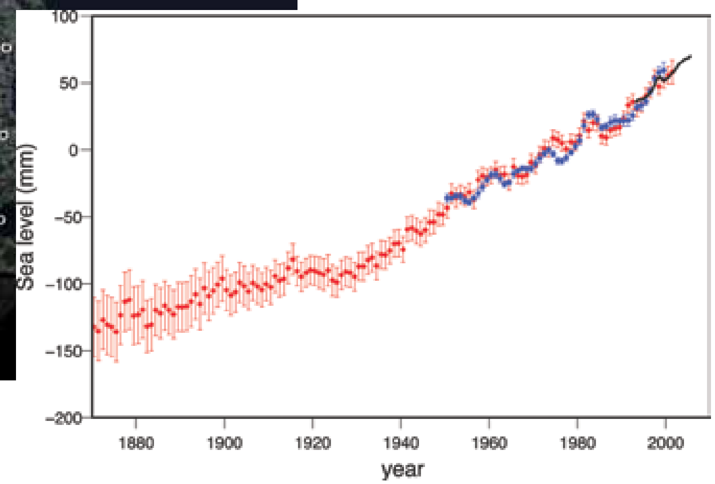
Climate changes over many time and space scales – from month to month, season to season, year to year, decade to decade, and century to century, globally and regionally. Monthly temperatures and precipitation statistics, generally based on 30-year spans of weather observations, describe the climate for cities around the world and are used every day by businesses and individuals in planning their activities – consider how climate information could influence your decision on what month to plan a Disneyworld vacation. Short term climate fluctuations, some caused by the occurrence of El Niño (see sidebar), can impact rainfall and temperatures over large regions of the Earth for months at a time. Droughts impact agriculture and can contribute to wide-spread famine in less developed countries. Climate fluctuations also have very local effects. For example, regions such as the Chesapeake Bay have climate indicators tailored to better understand fish mortality (see figure opposite page).

Long term changes in the Earth as a whole are described by several climate variables including globally-averaged temperature and sea level height (see figure opposite page). Changes in the Earth's climate can have large impacts on humanity, global economies, and major ecosystems. Scientists agree that the Earth has been warming since the industrial age, with increasing emissions of CO_2 and other greenhouse gases very likely the primary cause.

Satellite data are increasingly well-suited for climate measurements. STAR utilizes NOAA, NASA, and international satellite data to describe, monitor, and understand the Earth's climate.

Climate: Regional to Global





Top: Local climate information about the Chesapeake Bay from December 7, 2010 – January 7, 2011. The drop in temperatures from 44F to 36F is thought to have stressed many of the juvenile spot fish in the area, leading to their mortality. Bottom: Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870 (updated from Church and White, 2006); the blue curve shows coastal tide gauge measurements since 1950 (from Holgate and Woodworth, 2004) and the black curve is based on satellite altimetry (Leuliette et al., 2004). The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Error bars show 90% confidence intervals. (Image and caption from Figure 5-13, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change).

Earth radiation budget from satellites

In the past three decades, several dedicated NASA and European research instruments have measured the Earth's radiation budget. Because research missions have a finite lifetime, without guarantee of replacement, they cannot be relied on to provide the continuous, sustained observations required for monitoring changes in the Earth's radiation budget over the long term.

STAR scientists have developed techniques to measure the radiation budget from the observations of imager and sounder instruments onboard NOAA polar operational satellites, e.g., the Advanced Very High Resolution Radiometer and the High-resolution Infrared Radiation Sounder. The operational nature of NOAA satellites and measurements assures their long term continuity. Such a gap-free data record makes these measurements potentially valuable for monitoring long-term changes in the climate.

However, constructing a dataset for climate studies from these operational satellites is not trivial. Climate variations are much smaller in magnitude than typical weather changes. These smaller signals are more difficult to measure and require particular attention to instrument calibration and the long-term stability of the instruments. In addition, these instruments do not measure the total (all-wavelengths) radiation; instead they make observations in a limited number of narrow spectral regions. Models are used to convert these narrowband measurements to the quantity needed for radiation budget.

Earth Radiation Budget

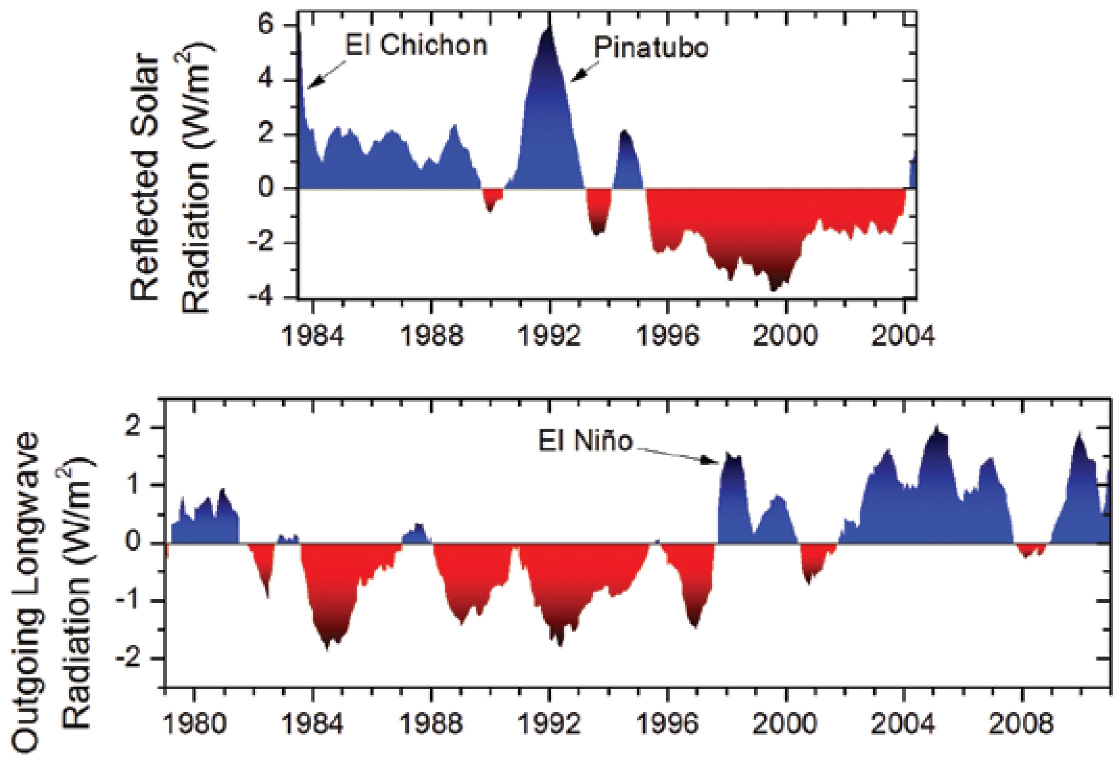
Istvan Laszlo and Hai-Tien Lee

The Earth receives energy in the form of radiation (sunlight) from the Sun. At the same time it also returns energy to space by reflecting back part of the incoming solar radiation and by emitting thermal – or infrared – radiation. The net difference between the energy received and that returned is the "Earth radiation budget".

The radiation budget varies both geographically and seasonally. For any given region and time the budget is usually not balanced, meaning some areas receive more energy than they return to space – for example, tropical areas – leading to warming, while others lose more energy than they receive – Polar Regions - leading to cooling. This north-south variation in energy input to the Earth is also the driving force for the major atmospheric wind patterns: the easterly trade winds in the tropics and the prevailing westerlies at temperate latitudes. Whether the budget is balanced on a global scale and over a long period of time is of paramount importance for understanding climate change.

The thermal radiation emitted to space is often referred to as the outgoing longwave radiation (OLR). Low OLR values are usually associated with thick, precipitating clouds, making OLR measurements a useful proxy for estimating precipitation. NOAA's Climate Prediction Center uses OLR data to monitor El Niños, and, more generally, OLR observations are used to diagnose, assess, and verify predictions of rainfall by climate models.

Changes in the Earth's Radiation Budget



The variability of the radiation budget is directly related to changes in the state and composition of the Earth's surface and atmosphere, especially changes in cloudiness. The top panel shows that during the period 1983-1995 the planet reflected more (blue color), while between 1996 and 2004 it reflected less (red color), solar radiation back to space than it did on average. The reflected amount was especially large during and following the eruptions of the El Chichon and Pinatubo volcanoes. The outgoing longwave radiation, shown in the plot in the bottom panel, also experienced sustained periods of excessive emitted radiation (blue color) during the strong El Niño episodes in 1998 and 2003-2007, and reduced emitted radiation (red color) during 1988-1997. The reflected solar radiation was derived from observations of operational geostationary and polar satellites as available in the International Satellite Cloud Climatology Project (ISCCP). The OLR data were derived from the High-resolution Infrared Radiation Sounder (HIRS) onboard NOAA's operational polar-orbiting satellite.

Greenhouse Gases

Chris Barnet

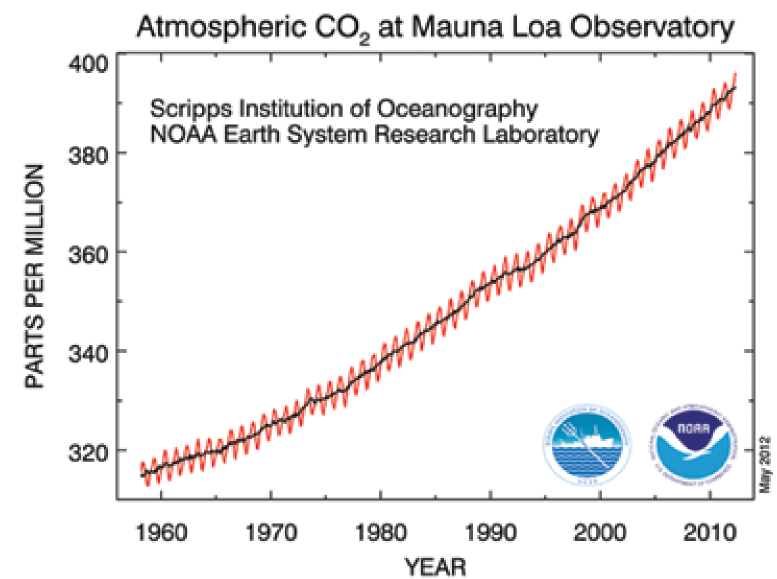
Natural variations of greenhouse gases are very large since the biosphere essentially breathes carbon dioxide in/out on daily, seasonal, and inter-annual time scales. Measuring the small long term change in carbon dioxide – a few parts per million/year – relative to this natural background is very difficult. Observations began in the 1950's by sampling the atmosphere with flasks. These are precise measurements, but they are labor intensive and, therefore, are only carried out at a handful of locations.

Satellites offer a global view of greenhouse gases (GHG), including the ability to identify and monitor sources of GHG emissions. Infrared instruments designed for weather applications have been used since the 1980's to measure carbon dioxide with some success. The basis of the technique is that, as a greenhouse gas, CO_2 reduces the Earth's emission of infrared (IR) radiation to space. The most recent advanced weather sounding instruments – hyperspectral infrared instruments – are sensitive to carbon dioxide, methane, and nitrous oxide and have shown continental scale changes in these gases. The European Union and Japan have launched satellites to measure GHG. The USA built the Orbiting Carbon Observatory (OCO) satellite, which was designed to accurately measure carbon dioxide; however, it failed to achieve orbit and a second attempt to launch an OCO instrument is being considered.

STAR scientists pioneered the retrieval of GHG information from the hyperspectral observations. Measuring GHG is an active area of research that most likely will require merging the space-borne observations and precise in-situ measurements with biosphere models to extract the GHG signal.

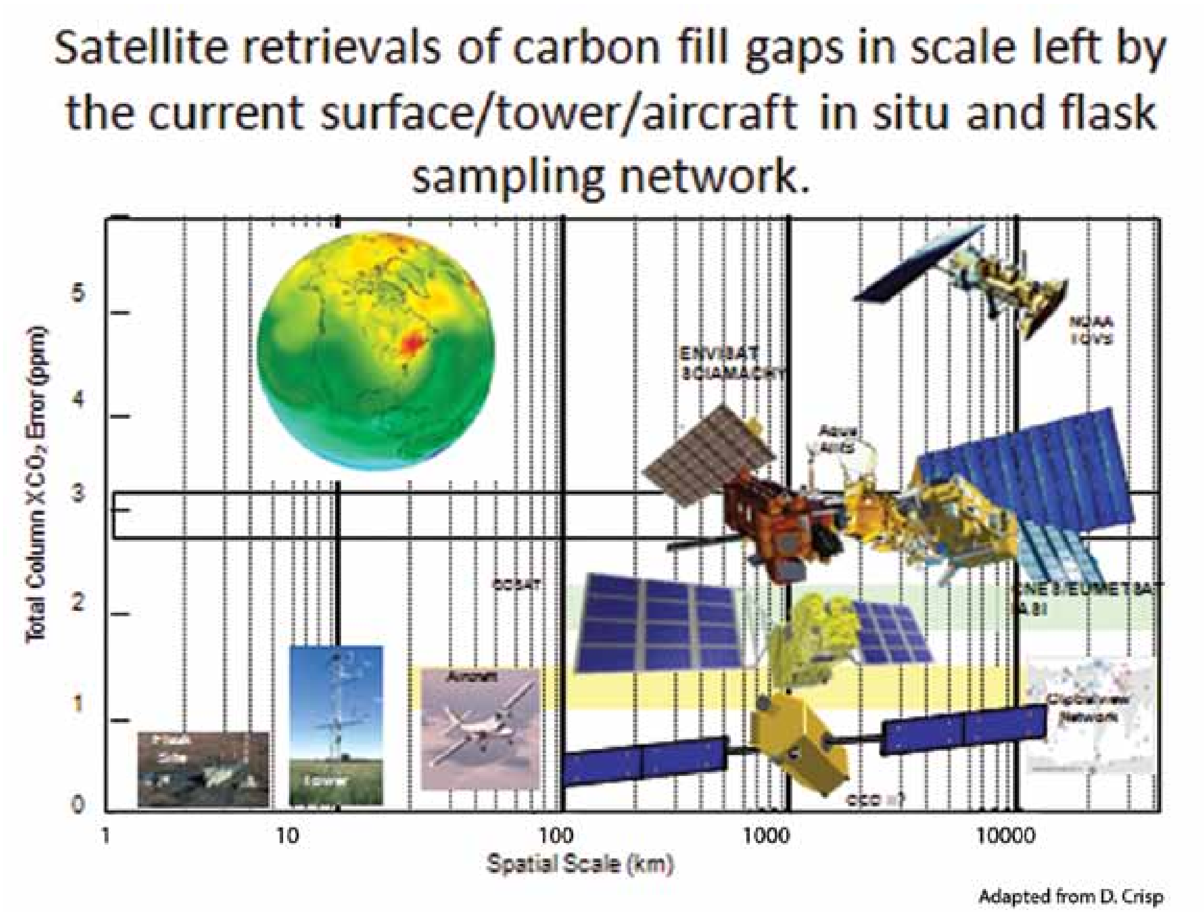
The most famous scientific curve of our time

Greenhouse gases warm the planet by trapping the heat – infrared (IR) radiation - emitted by the Earth. Adding a small amount of a greenhouse gas such as carbon dioxide, nitrous oxide, or methane can reduce our planet's ability to cool itself. All three of these gases are produced by the vital human activities of energy production, transportation, and agriculture. As a result, the amount of these gases has increased significantly in recent decades, with profound effects on the Earth's climate. The figure below shows the increase in atmospheric carbon dioxide at NOAA's observing station at Mauna Loa, Hawaii. Since the late 1950s carbon dioxide has increased by about 25%.



The most famous scientific curve of our time: the increase of atmospheric carbon dioxide (red: monthly values; black: seasonally adjusted data). (Photo credit: NOAA)

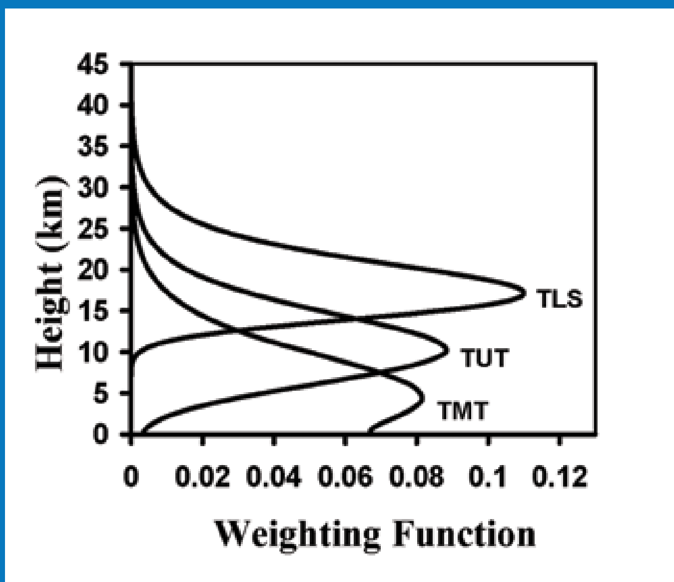
Observing Networks for Greenhouse Gases



The globe in the upper left is an example of a modeled CO_2 field (red, high values; blue, low values) during winter showing typical spatial patterns. The various instrument approaches are shown as a function of their precision (y-axis) and spatial scale (x-axis, km). In-situ measurements (flask sites, towers, and aircraft sampling) have the highest precision (lowest error) and tend to cover regional scales. Satellite instruments are less precise but allow continental scale measurements. Combining all the measurements into a network will likely result in high global precision.

What are layer temperatures?

The satellite microwave temperature sounding instruments measure radiation emitted by the surface and absorbed and reemitted to space by atmospheric oxygen at individual frequencies (wavelengths). The radiance (intensity of the radiation) measured at each frequency comes from a different layer of the atmosphere, depending on the strength of the absorption at that frequency. The percentage contribution of individual levels within the layer to the measured radiance is represented by a vertical weighting function of the temperatures in the layer.



The figure above shows the weighting functions for the temperatures of the mid-troposphere (TMT), upper troposphere (TUT), and lower-stratosphere (TLS) layers.

Atmospheric Temperature Trends

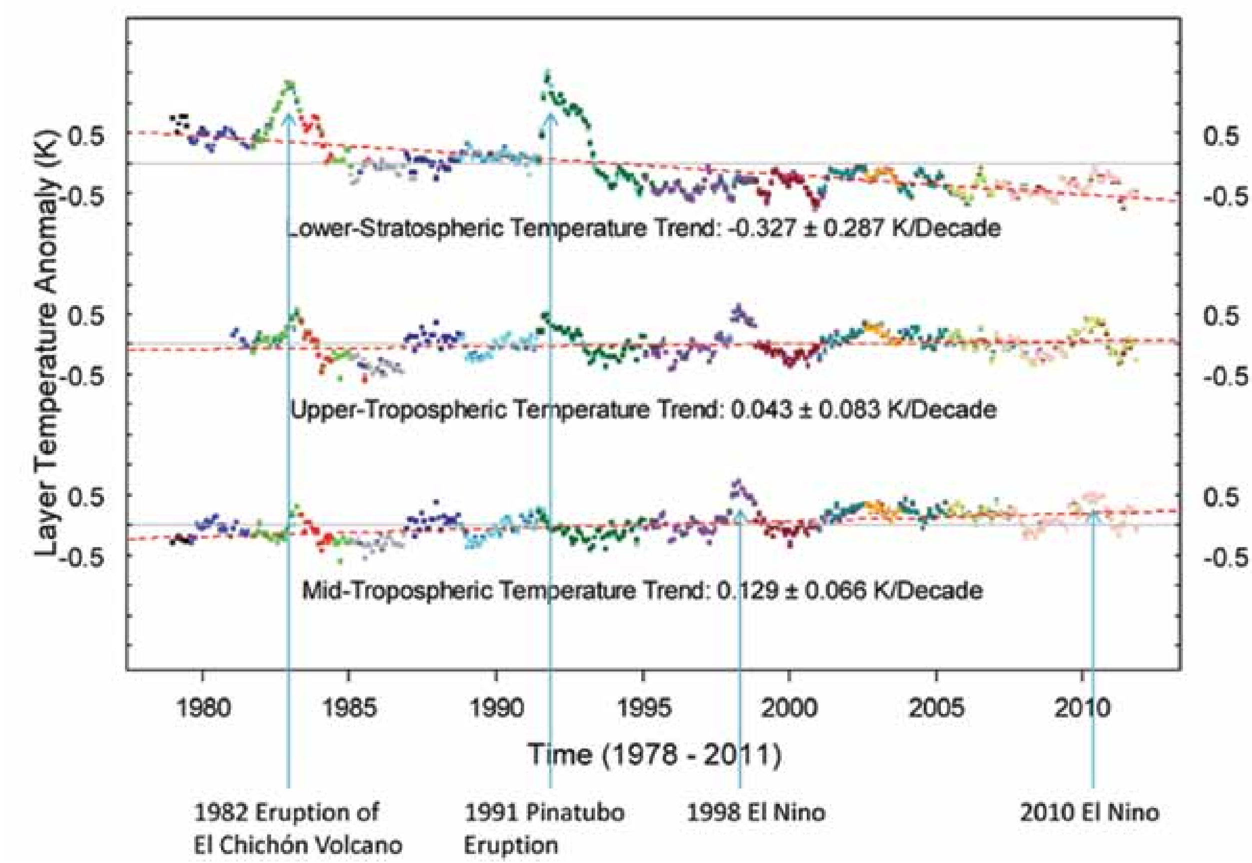
Cheng-Zhi Zou

Increases in atmospheric greenhouse gases such as carbon dioxide cause global warming of the Earth's surface and troposphere, and cooling of the stratosphere. The tropospheric temperature trend, which ranges from 0.1 to 0.2 °C per decade, is one of the most important indicators of the rate of global warming. Superimposed on the long term trend are shorter term (years) variations in global temperature due to phenomena such as El Niño/La Niña, intense volcanic eruptions, and natural variability. These shorter fluctuations, which can have amplitudes of a few tenths of a degree C, make temperature trend determinations very difficult. It may take over 30 years for the global warming signal to emerge from the "noise" of short term variability and be detected with confidence.

Since 1979, the microwave sounding instruments on polar-orbiting satellites have measured the temperatures of different layers of both the troposphere and lower-stratosphere. Compared to other observation systems, such as radiosondes and satellite infrared instruments, the microwave soundings have the advantage of long-term continuity, global coverage, and insensitivity to cloud effects. Since the observations are made from instruments on different satellites, good inter-satellite calibration is crucial to obtaining reliable temperature change values.

STAR's well calibrated data time series on the opposite page indicate that over the last three decades the middle-troposphere has warmed by 0.14±0.07 °C/decade and the upper troposphere by 0.04±0.08 °C/decade, while the lower-stratosphere has cooled at a rate of 0.33±0.31 °C/decade, where the plus-minus signs (±) indicate the uncertainties of the trends.

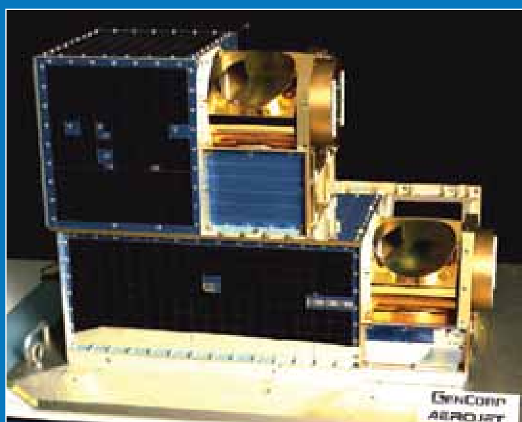
Variability and Trends of Atmospheric Temperatures



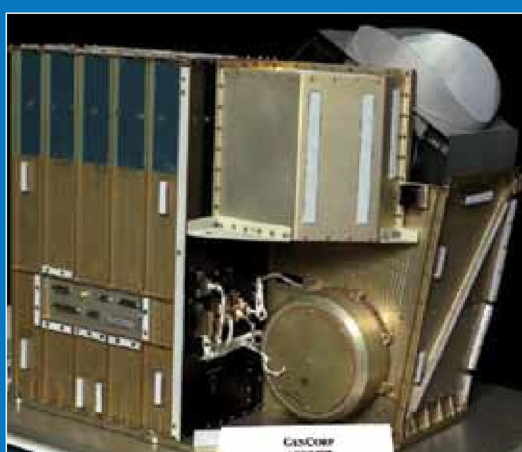
Monthly, global-mean temperature trends in the mid-troposphere, upper-troposphere, and lower-stratosphere. Colored dots represent recalibrated observations from different NOAA and MetOp-A polar orbiting satellites. The pink dashed lines represent the long-term trends of the time series. The temperature trend changes from a warming of 0.14 °C/decade of the mid-troposphere to a cooling of 0.33 °C/decade of the lower stratosphere. Signatures due to volcanic eruptions and El Niño are marked by arrows.

What does a microwave radiometer look like?

The AMSU-A is a cross-track scanning microwave radiometer consisting of two physically separate modules, each about 70 cm by 35 cm by 60 cm with a mass of about 50 kg. AMSU-A1 provides measurements at 13 different wavelengths and AMSU-A2 at an additional two frequencies. AMSU-A has a spatial resolution of 50 km and a scan width of 2300 km.



AMSU-A1



AMSU-A2

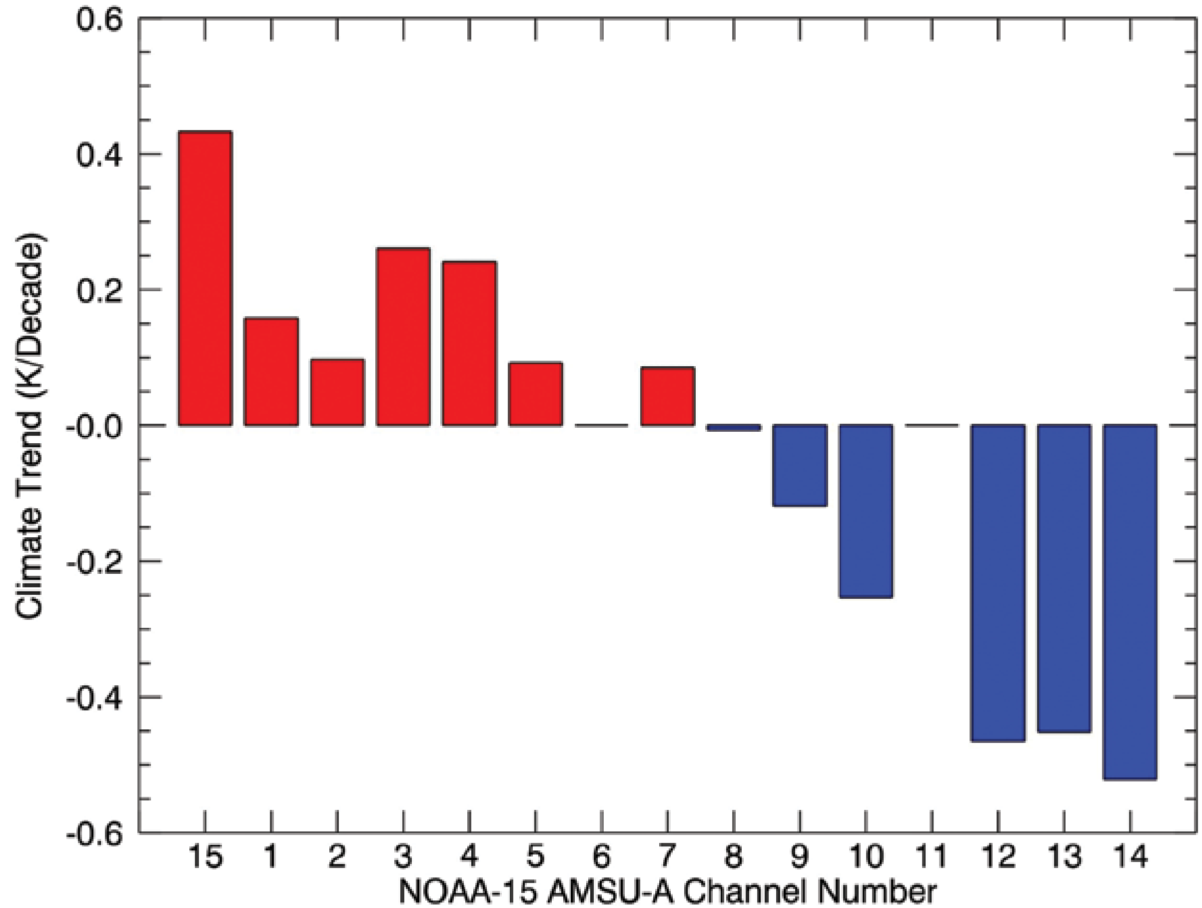
Trends in Temperature Profiles from a Single Instrument

Tsan Mo

The Advanced Microwave Sounding Unit-A (AMSU-A) was first flown on the NOAA-15 polar orbiting satellite. It observes the microwave (radio wavelengths) emission of the Earth at 15 different frequencies, which are absorbed by atmospheric oxygen and then re-emitted by the atmosphere to space. The measured radiance depends on surface and atmospheric temperatures, with each frequency sensitive to a different atmospheric layer. Having 11 more observing frequencies than the microwave sounder that it replaced, the AMSU presents an opportunity to monitor temperature trends in more atmospheric layers. The NOAA-15 AMSU-A performed measurements over its very long lifetime from May 1998 through December 2007. Although, for lack of absolute calibration standards in space, its absolute stability over this long time period is not possible to determine, STAR's analyses indicate that the NOAA-15 AMSU had good long term stability and its measurements could be used to derive long term climate trends.

STAR scientists have constructed a time series of global daily mean brightness temperatures – conversions of the observed radiation to emitting temperatures, which correspond to temperatures of atmospheric layers – of the near-nadir (directly below the satellite) measurements for the period. After removal of the typical annual cycle of temperature from the data, one is left with a time series representing the inter-annual and longer term trends in the temperatures. Linear trends fitted to the time series of the measurements at individual frequencies reveal that tropospheric layers are warming and stratospheric layers are cooling (see figure opposite page), in agreement with climate model simulations and with more sophisticated multi-sensor analyses, which have to account for inter-satellite biases.

Temperature Trends of Atmospheric Layers: 1998-2007



Temperature trends at multiple atmospheric layers derived from the NOAA-15 Advanced Microwave Sounding Unit data at different frequencies (channels) from May 1998 through Dec. 2007. Channel 15 measurements represent the layer closest to the Earth's surface, channels 1 – 8 represent temperatures at increasingly higher layers of the troposphere, and channels 9 – 14 represent increasingly higher layers of the stratosphere. The data clearly show the transition from tropospheric warming to stratospheric cooling, as predicted by climate models.

Historical sea surface temperature (SST) variations

Historical SST variations reconstructed by several international centers consistently show increasing global temperatures since the 19th century. The SST time series in the figure indicates a warming of about 0.6°C during the 20th century. We estimate that the uncertainty of this temperature change is about ±0.2°C, mostly due to sparse data and data bias early in the historical record. The 20th century increase is consistent with increases in independently analyzed land temperatures.

The figure (opposite page) shows large increases at high latitudes, consistent with many climate models that indicate greater warming in these regions. There are also large changes in the east tropical Pacific and Atlantic, regions that are typically cooler than surrounding areas due to upwelling of cool subsurface waters. Time series show the averages of both the historical analysis and the satellite-based data. The spatially complete satellite-based data are used to compute statistics used in the historical analysis. Comparison of the two shows that the historical analysis is able to resolve realistic SST variations.

Sea Surface Temperature Trends

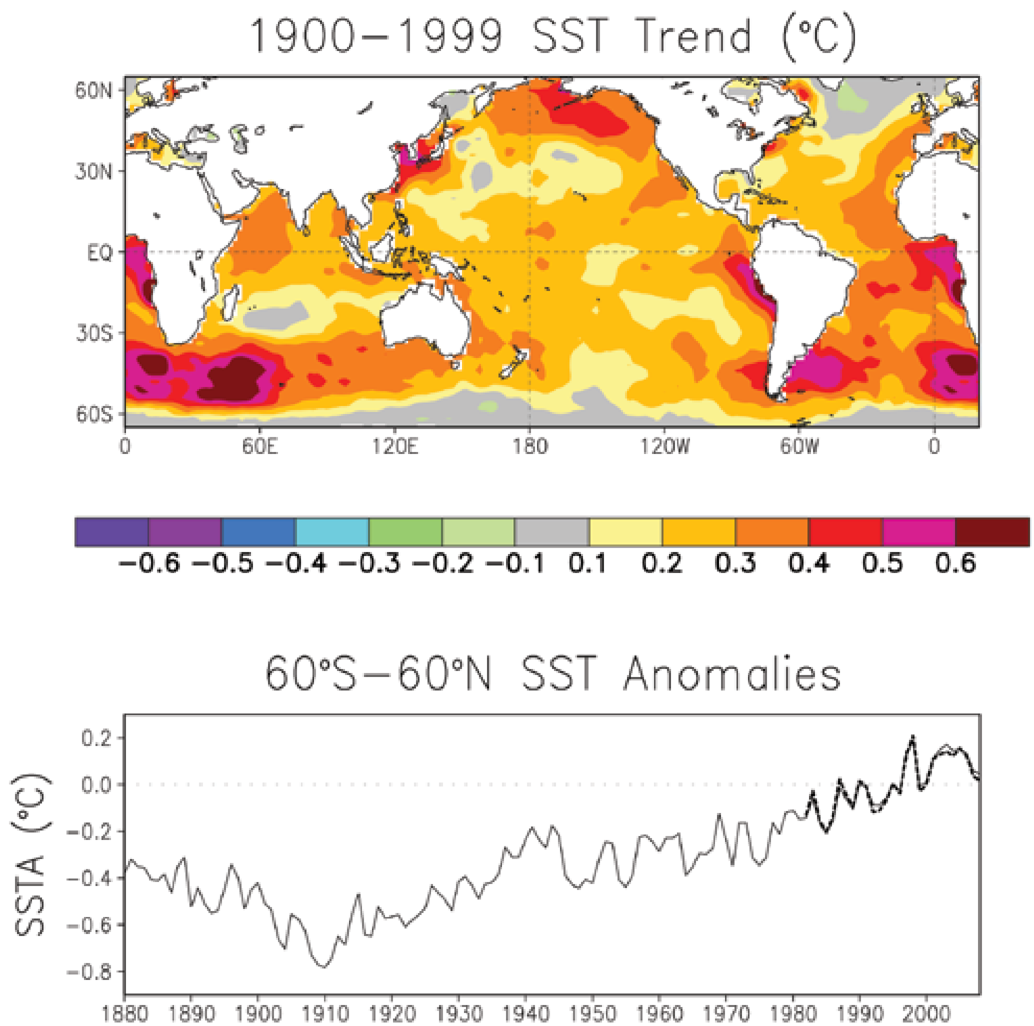
Thomas M. Smith and Richard W. Reynolds

The trend in global average surface temperature is the most widely used indicator of climate change. Since oceans cover about 70% of the Earth's surface, ocean temperatures should dominate, and are necessary to ensure accuracy of any analyses of global temperature variations. However, in contrast to land areas which have large numbers of weather station observations, the oceans are poorly observed. Prior to 1981, the major sources of sea surface temperature (SST) observations were merchant ships plying the world's trade routes. However, beginning with the launch of the Advanced Very High Resolution Radiometer on NOAA's polar orbiting satellites in 1981, satellite data have provided more complete coverage of the ocean surface. In addition, many buoys, both moored and drifting, have been deployed to measure SST since the 1980s. But then, how confident can we really be about ocean-only and thus global surface temperature estimates prior to the 1980s?

Analyses of the sparse and irregular early pre-satellite SST records are often referred to as reconstructions. Reconstructions analyze the data to a constant grid globally and over the analysis period. They are produced to evaluate climate variations over the historical period and as boundary conditions for climate models. Reconstructions require high-density modern data – such as those from satellite observations – to compute statistics needed to analyze the relatively sparse historical data.

The current version of STAR's SST reconstruction uses a satellite analysis merging in-situ and infrared-based satellite SST estimates to form base statistics that enable relationships between a sparse field of observations and a global analysis to be established. These relationships are used to reconstruct a time series of global SST from the sparse historical observations, dating from the late 1800s, to the present, which is used for climate monitoring and studies by national and international climate-research centers.

20th Century SST Trend



Near-global sea surface temperature (SST) variations. The geographical distribution of SST trends for the 20th century reconstruction is shown in the upper panel. The annual 60°S-60°N average over ocean areas is shown in the lower panel for the reconstruction and for the satellite-based analysis (heavy dashed line).

Cloudiness Trends

Andrew Heidinger and Mike Foster

Clouds play a critical role in regulating Earth's climate, heating the Earth by downward emission of infrared radiation while cooling the Earth through reflection of solar radiation. On average, the cooling effect of clouds is greater than their heating effect. Even small changes in this balance have implications for the Earth's climate. How clouds and their radiative effects will change as a result of greenhouse warming is a major source of uncertainty in model projections of future climate. The ability to make and sustain long-term measurements of cloud properties will provide climate scientists with data for monitoring cloud trends, constructing improved models of cloud processes, and checking climate model predictions.

STAR scientists have constructed a cloud record from 1981 to present based on data from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA's polar orbiting satellites. The record includes the following cloud variables: amount, height, temperature, and particle size and density. The processing framework and algorithms used to generate the cloud record also incorporate data from the more recent GOES imager satellite series. The stationary positioning of the GOES satellites relative to the Earth's surface allows for the continuous observation of how cloud patterns change throughout the day at a single location, contributing valuable information to the climate records.

The accompanying figure shows that global cloudiness has decreased since 1981 at a rate of 0.51%/decade, with an uncertainty of +/- 0.42%/decade. Since clouds generally act to cool the Earth, a decrease in cloudiness would enhance the greenhouse effect due to human activity.

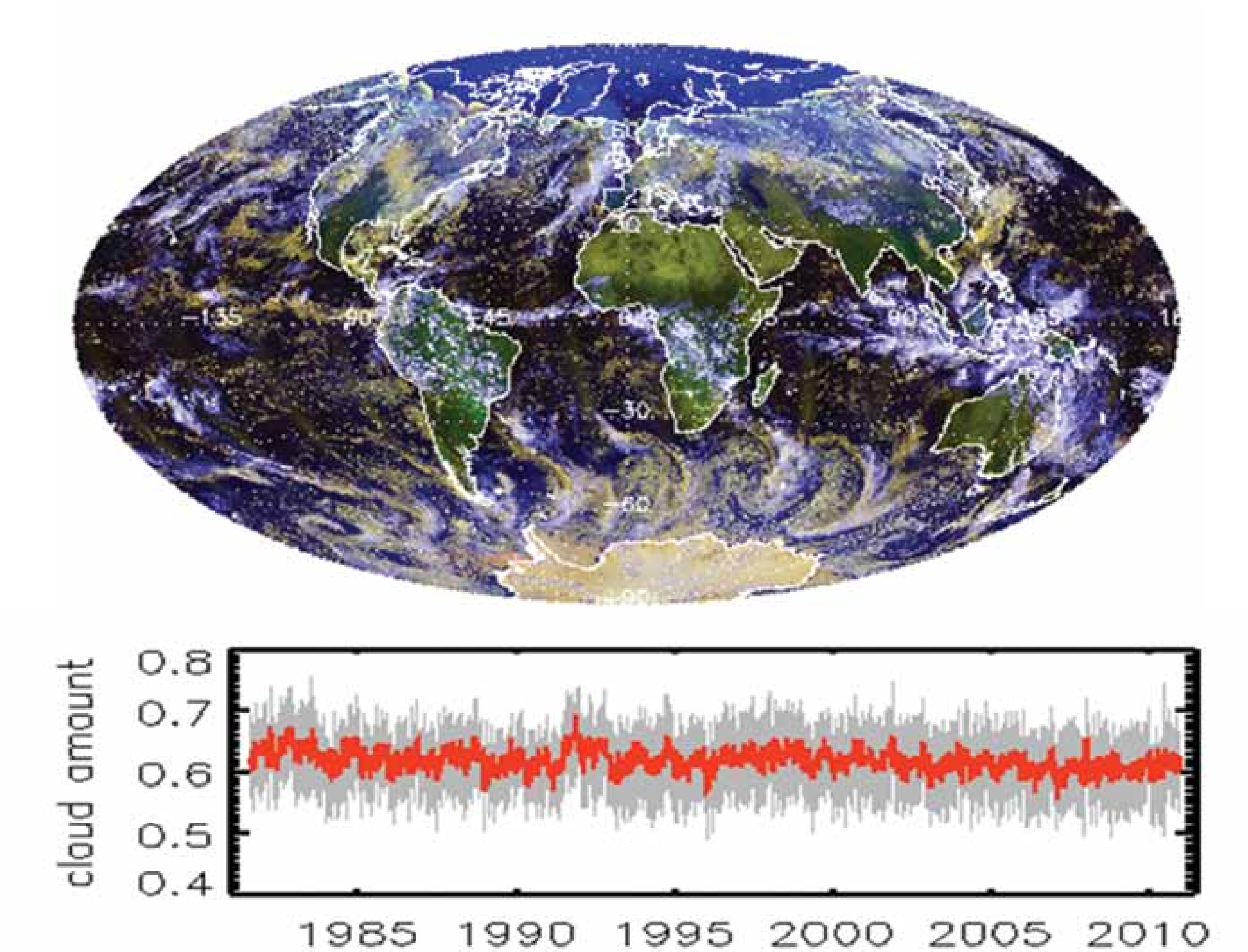
Challenges in detecting long-term changes in cloudiness

Identifying long-term signals, or trends, in a satellite cloud record can provide some interesting challenges. The longest satellite records span roughly three decades, which from a climate perspective is a relatively short period of time. What this means in practical terms is that short term phenomena that affect global cloudiness, such as the El Niño-Southern Oscillation and major volcanic eruptions, can mask potential long-term signals.

There are also challenges related to the satellites themselves. For example, as time passes, polar-orbiting satellites sometimes drift away from their original paths, causing a slow shift in the local time of day at which they observe the Earth. This can cause the phenomenon known as aliasing, which could lead to artificial trends in the data.

Aided by the lengthening cloud record and advanced measurements from more recent satellites, STAR researchers are overcoming these challenges and providing an accurate long-term cloud climate record.

Cloudiness Record over the Satellite Era

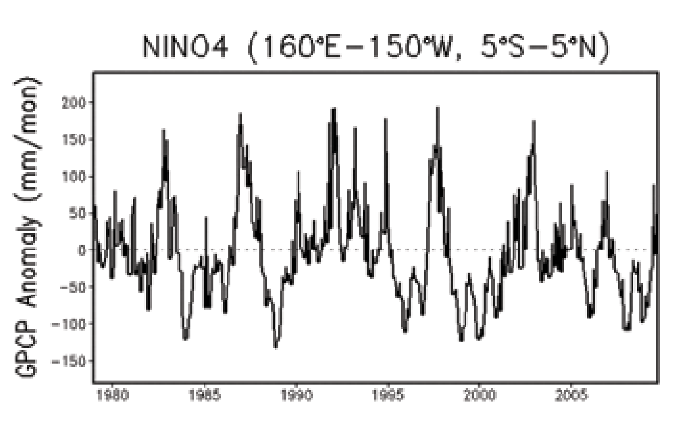


Upper panel: a false-color global image using three channels (red=visible, green=near-IR, blue=infrared) used to detect clouds and their properties. Lower panel: time-series (red), including an uncertainty estimate (grey), of mean global total cloudiness anomaly (60°S-60°N) spanning the AVHRR satellite record. The data indicate that global cloudiness has decreased at rate of 0.51%/decade, with an uncertainty of +/- 0.42%/decade.

Is the Earth's precipitation changing?

Arguably, precipitation is the most critical climate variable affecting humankind. Data sets such as the Global Precipitation Climatology Project (GPCP) are valuable for studying interannual climate variability due to phenomena such as El Niño and La Niña. The figure shows the monthly anomalies (departures from normal) in rainfall over the tropical Pacific Ocean – values greater than zero correspond to El Niño events while those less than zero correspond to La Niña.

Global trends, however, are difficult to determine, since the small changes averaged over the entire Earth are still within the uncertainty in the data set. The figure shows no clear increase or decrease in the rain over the 30 year period 1979 - 2008. The uncertainty in the time series arises from the varying sources of data used over the three decades, each with its own set of measurement errors.



Global Precipitation Monitoring

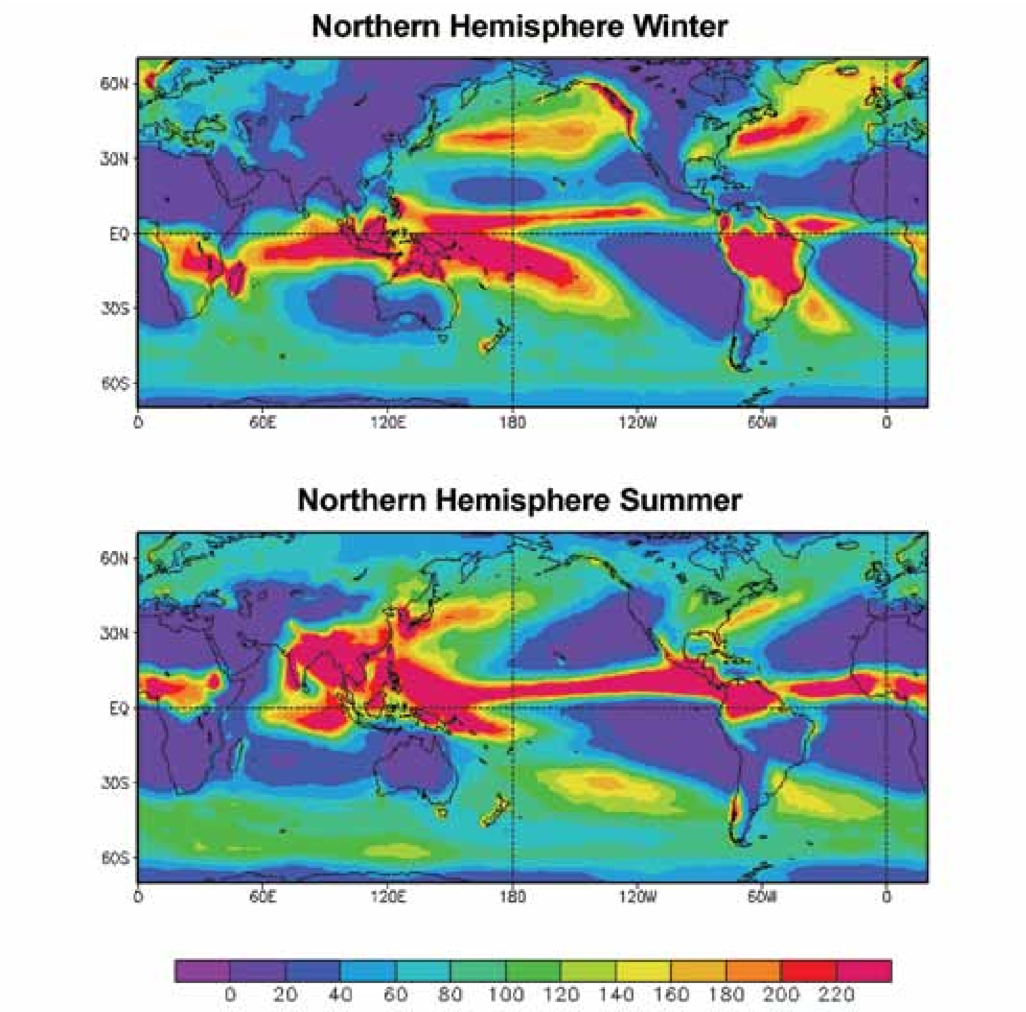
Ralph Ferraro, Robert Adler, Phillip Arkin, and Arnold Gruber

Precipitation – rain, snow, drizzle, hail, sleet and other variants – is the result of water vapor in the atmosphere condensing and falling to the Earth's surface. Extended periods of months or years of deficient rainfall may result in drought, often with significant social and economic consequences, regionally and globally. Seasonal and interannual fluctuations in rainfall and droughts are related to climatic variations such as El Niño (see sidebar). On longer time scales, the intensity and geographic distribution of rainfall will likely be significantly altered due to greenhouse warming.

A wealth of high quality surface measurements of precipitation from rain gauges and weather radars exists. The problem is that these measurements are concentrated in populated land areas, while large regions of the world, in particular the oceans, are poorly observed. Satellite observations have been utilized to complement the surface reports and fill in these large observational gaps.

A project called the "Global Precipitation Climatology Project", or "GPCP", an international effort lead by scientists at NASA and NOAA, in which STAR scientists play a leading role, has developed a series of global precipitation data sets that combine geostationary and polar orbiting satellite measurements from infrared and microwave sensors, along with high quality rain gauges, to produce a 30-year (1979 to 2008) global climatology. This data set has become the most widely accepted precipitation data set by the scientific community and is used to monitor seasonal to interannual precipitation variability and longer term trends over the past few decades.

Average Rainfall



Seasonal rainfall climatologies (mm/month): the top panel is for the Northern Hemisphere winter season (December, January and February), while the bottom is for summer (June, July and August). Note the northward movement of the tropical rain belt from NH winter to summer, the development of the south Asian monsoon in NH summer, and the oceanic precipitation associated with mid-latitude storms in the winter seasons of both hemispheres.

Water vapor and the greenhouse effect

Without infrared absorbing gases in the Earth's atmosphere, the surface temperature would be some 33 degrees Celsius cooler that it is now. Water vapor is the most important infrared absorbing gas, causing most of the Earth's natural greenhouse effect. Carbon dioxide's contribution to the natural greenhouse is only about 30%, but it is the increasing industrial emissions of CO_2 that are causing global warming. However, due to the water vapor feedback – more water vapor with higher temperatures – total global warming is actually double that produced by CO_2 alone.

Consistent with the above reasoning, the satellite data (opposite page) indicate that atmospheric water vapor is increasing. The figure shows the variations in total precipitable water – the total water vapor in a vertical column of the atmosphere – between 1991 and 2006. Water vapor is increasing at a rate of about 0.3 mm/decade – or about 1%/decade – over the global oceans and 0.6 mm/decade over the tropical oceans. These results are significant at the 99% level (only one chance in a hundred that they are due to chance).

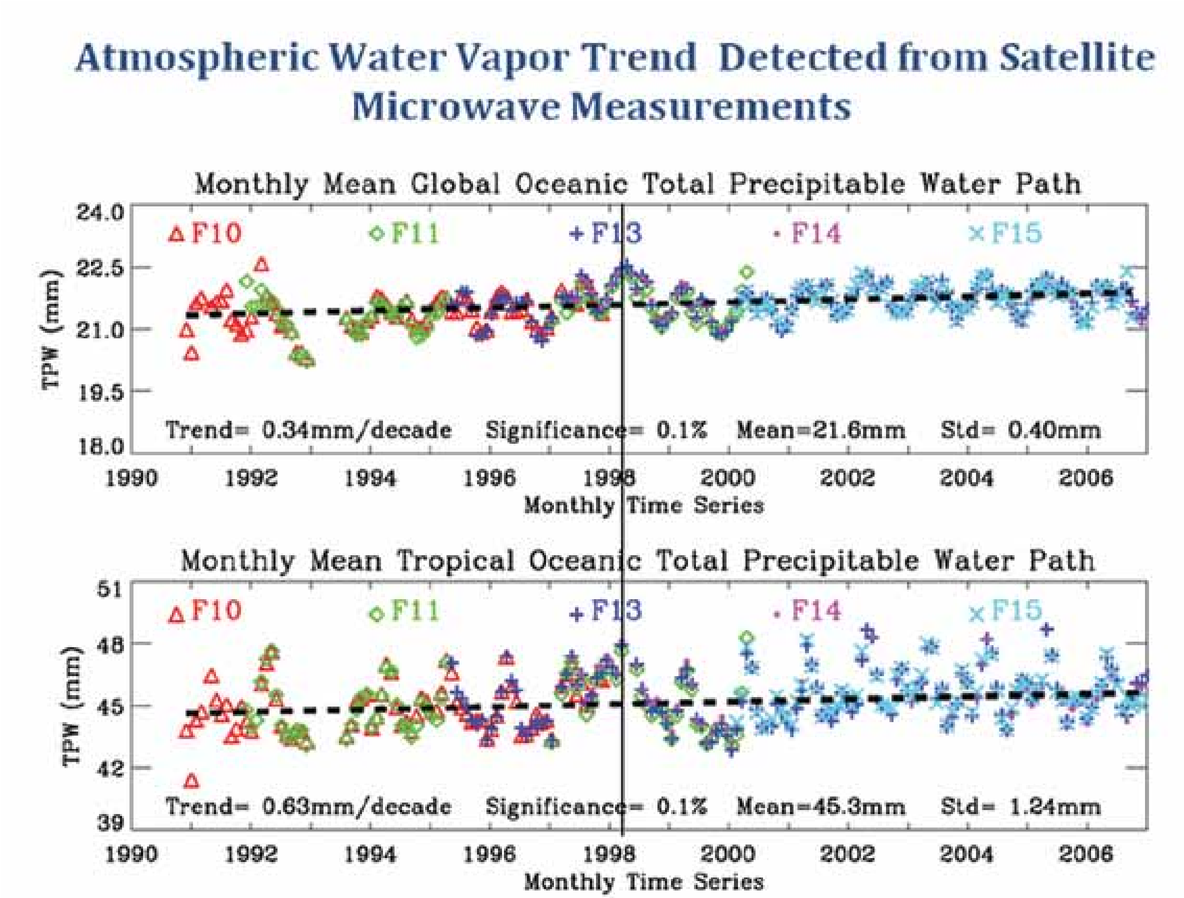
Water Vapor Trends

Fuzhong Weng

In addition to its importance for cloud formation, precipitation, and the hydrological cycle, atmospheric water vapor plays a crucial role in anthropogenic warming. A warmer atmosphere due to increasing greenhouse gas emissions can hold more water vapor. As a strong absorber of infrared radiation, the increased water vapor significantly amplifies the initial anthropogenic heating, leading to increased temperatures.

Retrievals of column-integrated water vapor from Department of Defense's Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) series are generally regarded as providing the most reliable measurements of water vapor over the global oceans. The long-term multiple SSM/I measurements – since 1987 – cannot be simply stitched together to create a time series of water vapor variations. Inter-sensor systematic differences arise from multiple factors such as slight variations in instrument characteristics, satellite orbital drifts, and missing measurements during their observational periods. Using the DMSP F13 satellite as a reference satellite with longevity, the mean differences between other satellites and F13 are derived. If there are no coincident measurements of the F13 and another satellite, a third satellite that intersects the F13 orbit is used as a transfer radiometer. This cascaded approach has been applied to all the SSSM/I sensors on the DMSP satellites –F10, F11, F13, F14, and F-15 – from 1991-2006 to derive the stable water vapor time series shown on the opposite page.

Water Vapor Trend



Monthly values (symbols) and trends (dashed lines) of the total precipitable water vapor (TPW, the total water vapor in a vertical column of atmosphere) over the global and tropical oceans from microwave observations of Defense Meteorological Satellite Program (DMSP) satellites (different colors). Note the positive trends and the amplitudes of the inter-annual fluctuations, particularly the positive anomaly associated with the El Niño of 1997-98 (vertical line).

Why is sea level rising?

While satellite radar altimeters measure changes in sea level, they don't explain why the ocean is rising or falling. An accounting of the major processes that cause sea level change is often called the sea level budget.

Two new observing systems have recently been put into operation that complement sea level data from altimeters and allow the sea level budget to be assessed. The first, Argo, is an array of 3000 robotic floats that monitor temperature and salinity in the upper part of the ocean. The second, the Gravity Recovery and Climate Experiment (GRACE) satellite mission, measures changes in the Earth's gravity field and can "weigh" the ocean every month.

Together, measurements from the Jason series of altimeters, Argo, and GRACE allow sea level variations to be separated into sea-level change from changes in ocean-water density caused by heat and freshwater, and changes in ocean mass that reflect the exchange of water between the ocean and land (such as glaciers, ice caps, ice sheets, and ground water). When the observations from all three systems agree, the sea level budget is said to be "closed" or balanced".

Sea Level Rise

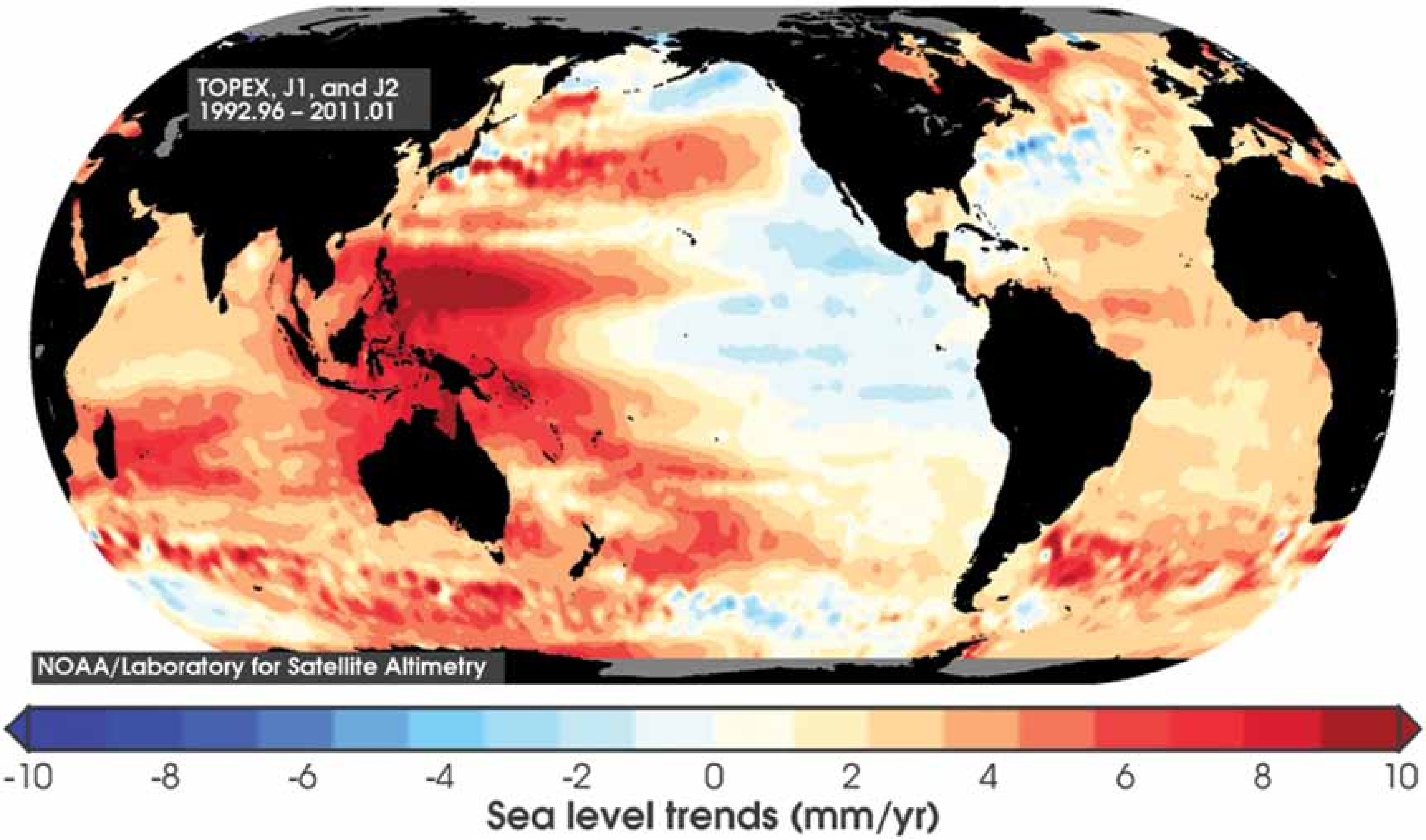
Eric Leuliette

About thirty percent of the United States population lives near the ocean, and worldwide roughly 200 million people inhabit coastal floodplains less than one meter above current sea level. The continued rise of the oceans will cause these low-lying regions to experience permanent inundation, repeated flooding, faster erosion of cliffs and beaches, increasingly saline estuaries, and salt contamination of groundwater.

As global temperatures increase, sea level rises for two major reasons. First, most of the Earth's heat is stored in the ocean and additional heat causes sea water to expand. Second, as glaciers and ice sheets on land melt, the ocean gains the additional water. While each of these processes contributed about the same amount to late 20th century sea level rise, additional warming will accelerate sea level rise due to increased melting of continental ice.

Most estimates of 20th century sea-level rise have depended on averaging the rates of rise from the few, long, high-quality tide-gauge records that are available. Since 1992, radar altimeters carried on satellites have measured sea level with an unprecedented accuracy, providing nearly global coverage of the world's oceans every ten days. Data from these satellite missions allow STAR scientists to monitor global and regional sea level rise more accurately than is possible from the sparse array of tide gauges. The map of sea level trends (opposite page) revealed by 18 years of altimetry shows a highly non-uniform spatial pattern, partly driven by natural decadal changes in circulation and ocean's thermal structure. STAR scientists use these data in combination with other ocean observations to understand the causes of the sea level rise.

Sea Level Rise



Trends in sea level from 1993–2010 as measured by the satellite radar altimeters TOPEX/Poseidon, Jason-1, and Jason-2. As a global average, sea level has risen at a rate of 3.2 ± 0.4 mm/year during this period. Regional variations are significant, with sea level falling in the east Pacific, while parts of the west Pacific have risen by more than 10 ± 0.4 mm/year.

The hole in the ozone layer

Ozone is an unstable gas consisting of three Oxygen atoms; O_3. Although O_3 is a very minor component of the atmosphere – its fraction of the air is measured in parts per million – it is critical in blocking most of the harmful Ultraviolet Solar radiation from reaching the Earth's surface. Ozone is distributed throughout the atmosphere but it is mainly concentrated in the lower and middle stratosphere, often called the Ozone Layer.

During the 1980s and 1990s, increasing levels of chlorine and bromine – caused by release of man-made chlorofluorocarbons (CFCs) – led to chemical reactions that destroyed stratospheric ozone molecules, resulting in world-wide decreases in ozone amounts at a rate of approximately 4% per decade. These ozone destroying chemical reactions are enhanced by the presence of Polar Stratospheric Clouds in the Antarctic Spring leading to the formation of a dramatic Antarctic Ozone Hole each year (See the time series of ozone hole images on the opposite page).

Restrictions on the production and release of CFCs following the Montreal Protocol of 1987 and subsequent amendments have been effective in reducing the abundance of these chemicals so that their levels in the stratosphere peaked in the early 2000s. Even though the concentrations of ozone-depleting chemicals are decreasing, their long lifetimes in the stratosphere ensure that it will be decades before their levels are below that needed to create an Ozone Hole.

Monitoring the World's Ozone

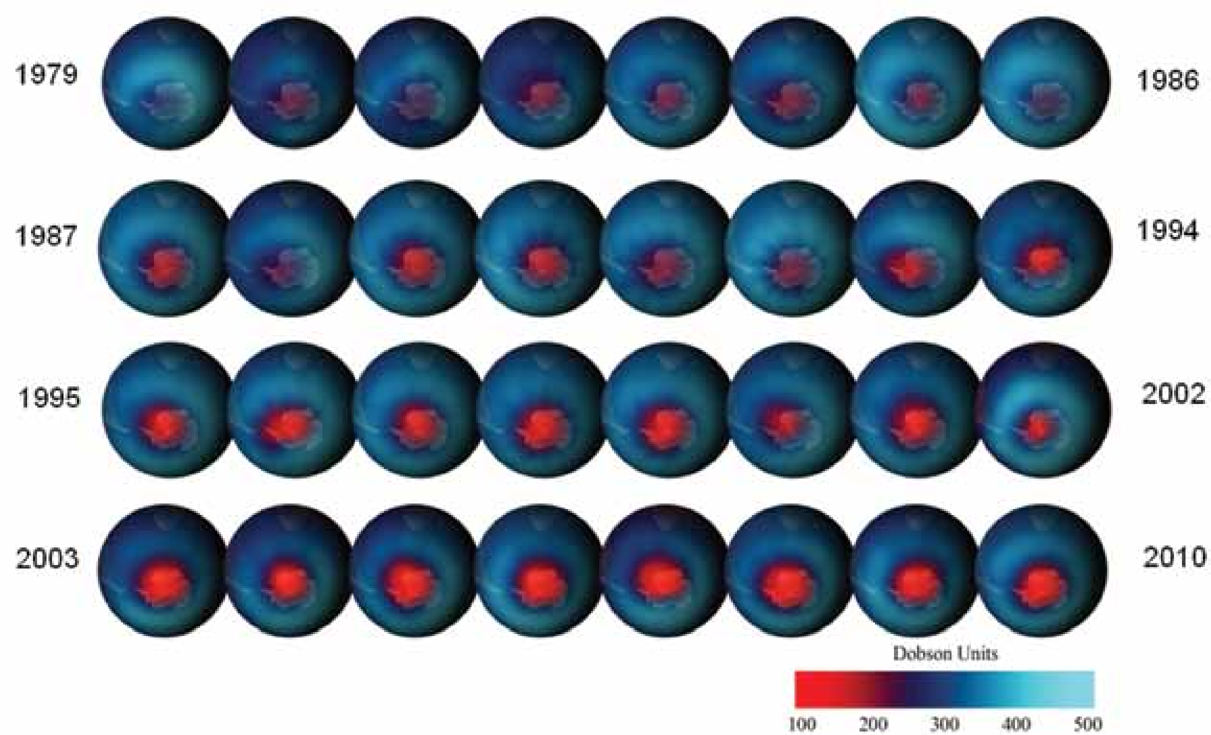
Larry Flynn and Craig Long

NOAA instruments measuring the amount of ultraviolet sunlight scattered back to space are part of a global system to monitor the world's atmospheric ozone levels. Seven Solar-Backscatter UltraViolet Spectrometers (SBUV/2 instruments) have flown on NOAA polar satellites since 1985. Their observations are used to generate total column ozone and ozone vertical profiles. These measurements are used in a number of applications: issuing Ultraviolet Index (a measure of sunburn risk) warnings; monitoring the ozone hole (see sidebar) from year to year, assimilation into weather and climate forecast models, and providing global assessments of the state of the ozone layer that are published every four years in the World Meteorological Organization Scientific Assessments of Ozone Depletion. The last instrument in this series was launched in February of 2009 and is performing well.

The ozone record from the SBUV/2 instruments will be continued by the next-generation Ozone Mapping and Profiler Suite (OMPS). The OMPS measurements will also provide a capability to make more detailed estimates of the vertical distribution of ozone. Researchers will make use of these improved values, over the next two decades, to investigate interactions between global climate changes and the expected recovery of ozone levels from the depletion caused by man-made chemical releases.

The figures on the opposite page show a time sequence of ozone measurements from the SBUV/2 instruments for the Southern Hemisphere documenting the evolution of Antarctic Ozone Holes since 1979. The colors represent different total amounts of ozone present from the bottom to the top of the atmosphere. Areas with the largest amounts of ozone are light blue and those with the lowest amounts are red.

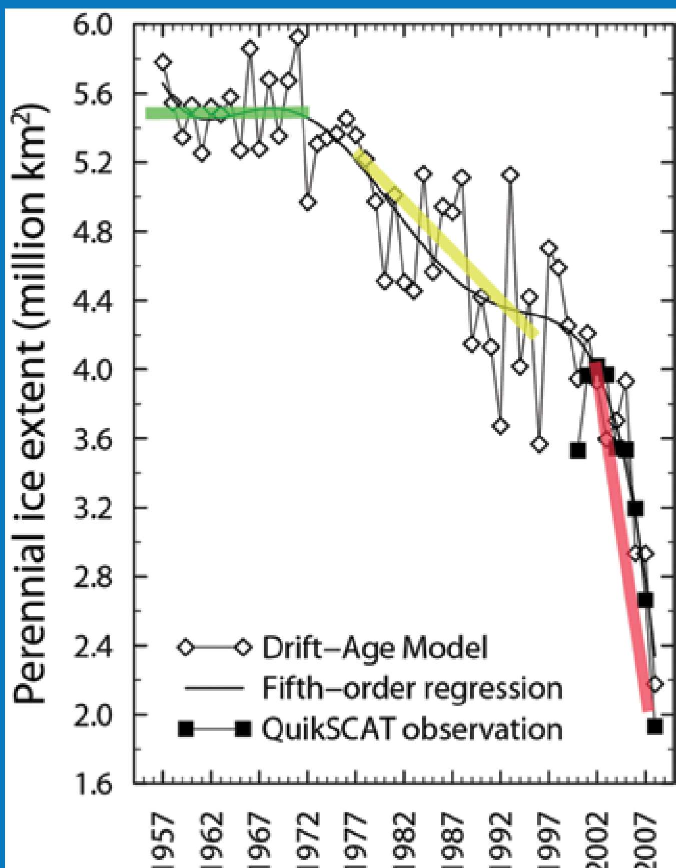
The Antarctic Ozone Hole: 1979 to 2010



Average monthly total column ozone (1 Dobson unit = 1 matm-cm of O3) in October from 1979 (top left) to 2010 (bottom right). The red-colored regions represent ozone amounts below 220 Dobson Units. These low values define Ozone Hole conditions. The variations from one year to another are influenced by the size and temperature of the Antarctic Polar Vortex (weather) while the general increase in Ozone Hole sizes during the late 1980s and early 1990s is related to the buildup of atmospheric chlorine and bromine from man-made chemical releases. Data prior to 1989 are from the NASA Nimbus-7 SBUV instrument.

A nose–dive in Arctic multiyear ice extent

The decrease in multiyear ice (MYI) extent – sometimes referred to as perennial sea ice cover – has accelerated in the last decade as captured by 1957-2008 buoy drift and age model, and scatterometer satellite data. Observations indicate that 2009-2011 perennial ice extent has remained low.



Arctic Sea Ice Cover Trends

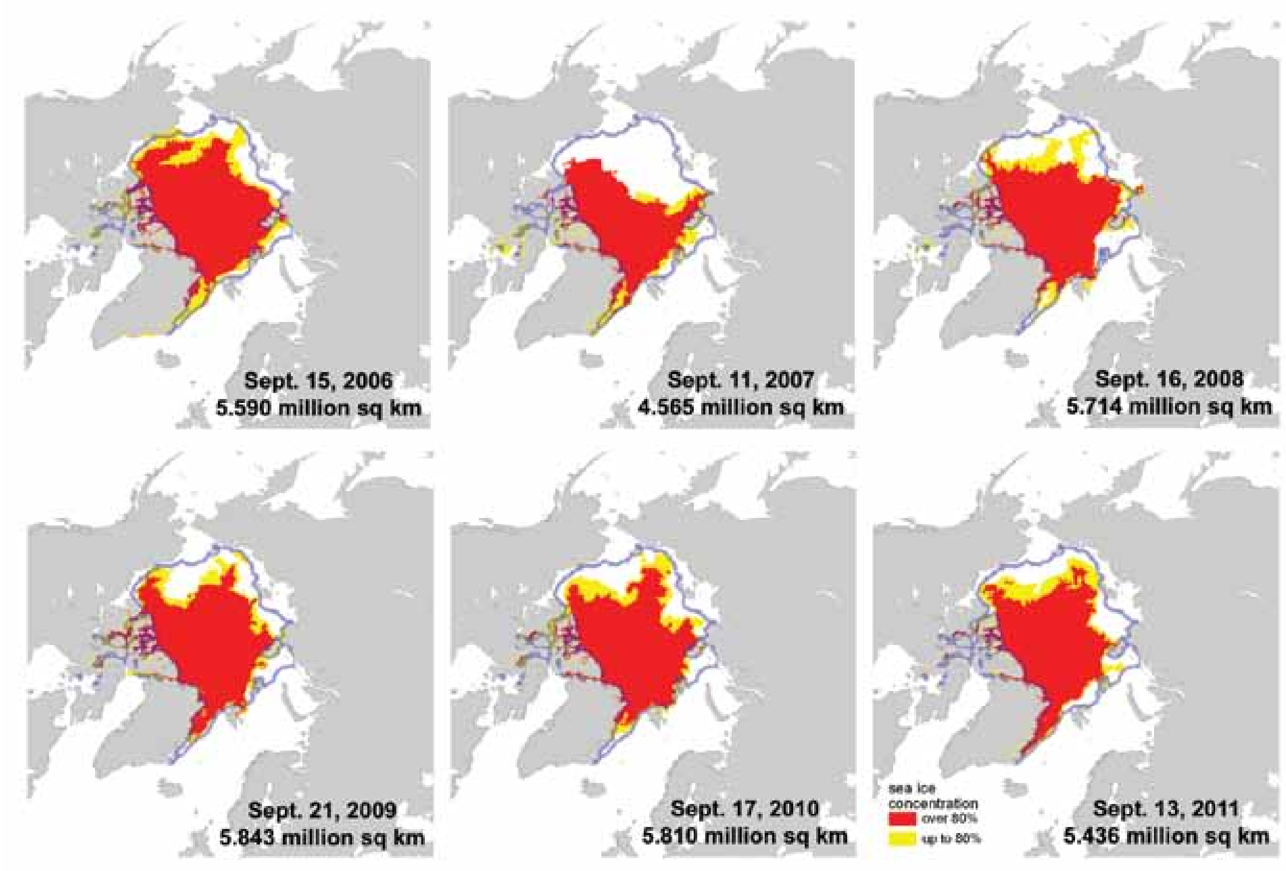
Pablo Clemente-Colón

Satellite observations indicate that the Arctic Ocean sea ice cover has been retreating rapidly during the last four decades – much faster than climate models have suggested. The synoptic capabilities of polar-orbiting environmental satellites have provided a unique view of changes over this region. The effects of global warming appear to be magnified in the Arctic with temperature increases more than twice as large as those in lower latitudes. Changes in the Arctic are not only an indicator of climate change but in turn have feedbacks on the global system.

The significant retreat of the Arctic sea ice pack in recent years has been documented using satellite data (see figure opposite page) with record low and second lowest minimum extents observed in summer 2007 and summer 2011, respectively. In fact, 4 of the last 5 summers have had sea ice extents falling even lower than the downward trend line. Furthermore, Arctic sea ice cover is experiencing a downward trend not only during the summer minimum but also during the winter maximum extent period according to the satellite observations.

While the rapid retreat of the overall Arctic sea ice cover is widely recognized, a similarly rapid loss of the multiyear ice (MYI), which is the oldest and thickest part of the ice cover, is not as well known by the public. The dramatic loss of MYI (see sidebar) in both extent and age (i.e., thickness) and the increased prevalence of seasonal ice in the pack contribute to a dramatic overall reduction of the Arctic sea ice cover mean thickness. In addition to changes in sea ice extent, summer melt appears to be occurring earlier in the season, with freeze-up occurring later in the fall.

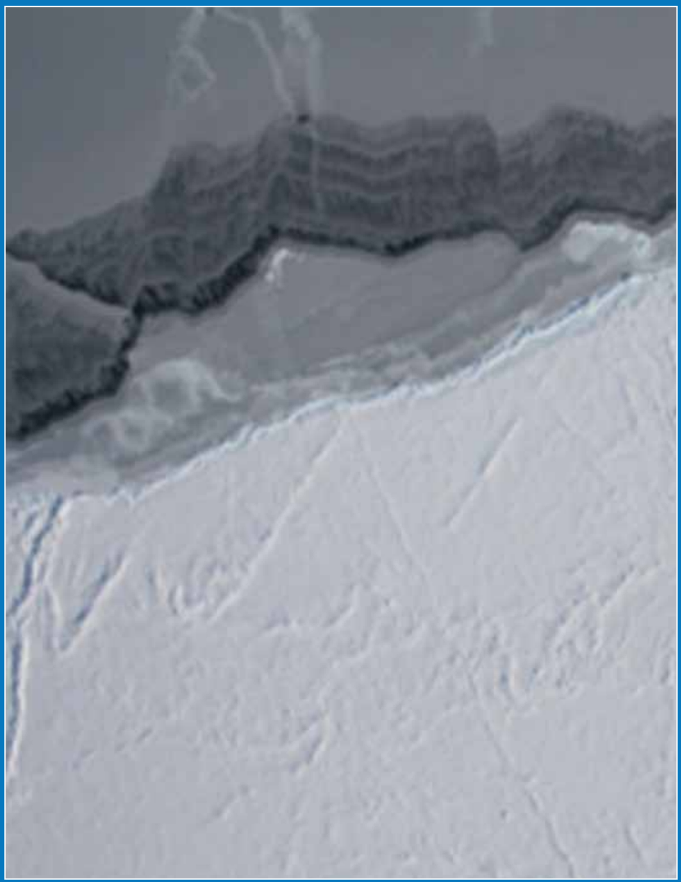
Arctic Sea Ice Extent Summer Minima



National Ice Center ice charts derived from daily analysis of multi-satellite imagery showing that the Arctic sea ice extent minima at the end of the 2006-2011 summer melting seasons fell well below the 1972-2007 September climatology median extent (indicated by the translucent blue overlaid line). The red areas represent pack ice characterized by sea ice concentrations of 80 per cent and above, yellow areas represent the marginal ice zone characterized by sea ice concentrations below 80 per cent, and white areas represent ice-free waters. Dates of minimum ice extent and the areal ice coverage at those times are included in the charts.

Thinning ice

In the coming decade, satellite altimetry will track whether Arctic sea ice continues to thin and what role this ice will play in any future global warming.



Digital Image of sea ice in the Canada Basin (April 21, 2009) from the NASA P3B aircraft. Gray area (upper left) is a refreezing stretch of open water. White area is a snow-covered, ridged area of older ice. (Photo credit: NASA)

Arctic Sea Ice Thickness

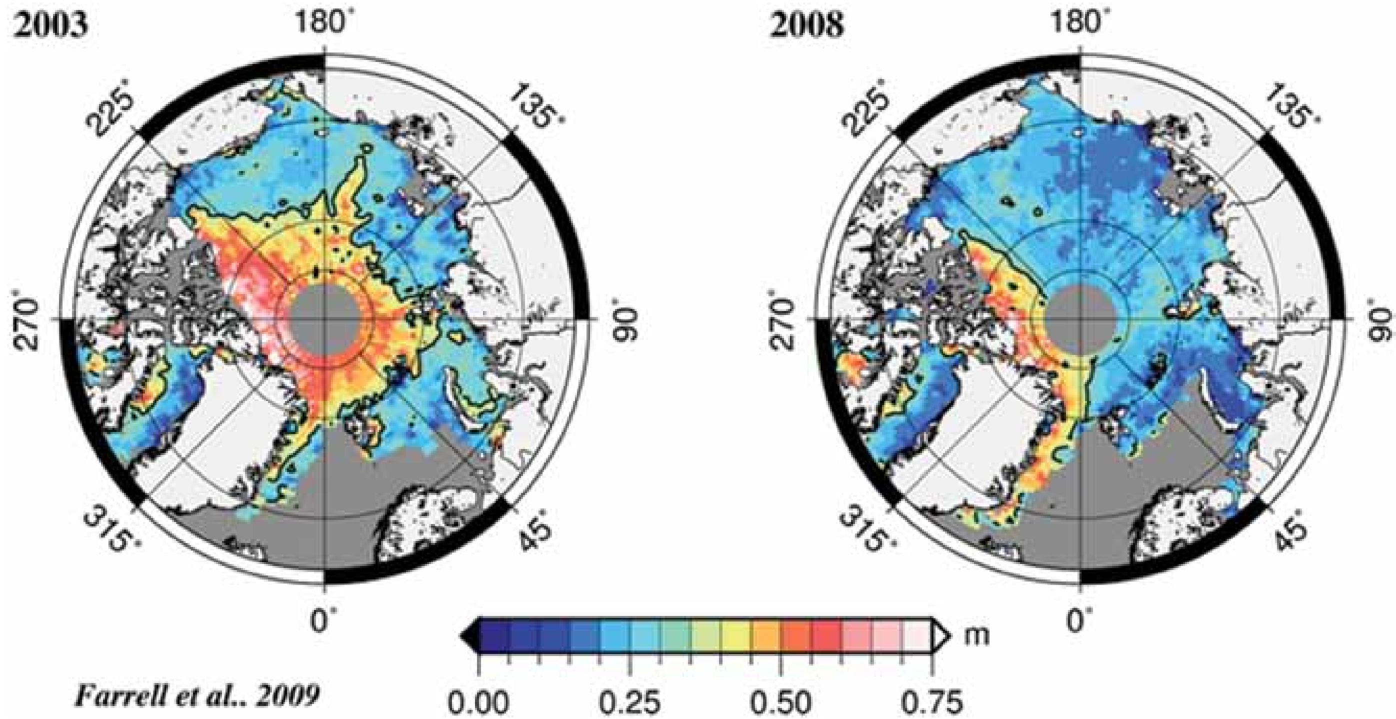
Dave McAdoo, Sinead Farrell, and Larry Connor

The floating sea-ice cover or "pack ice" is the defining feature of today's Arctic Ocean. Sea ice volume and thickness are important climate parameters and widely accepted as an important component of climate change owing, in part, to an ice-albedo (reflectivity) feedback mechanism: ice, which reflects most solar radiation is replaced by open ocean, which absorbs most solar radiation, thus amplifying any greenhouse warming.

While passive microwave satellites closely track the decline in sea ice area, they do not observe thickness changes. Evidence for associated thinning (or thickening) of the ice pack has been at best, equivocal, until quite recently. Upward-looking sonar (acoustical radars) observations from submarines since the late 1950's indicate some thinning albeit with limited spatial and temporal coverage. Other recent, but quite sparse, surface observations show thinning in the past 5 years.

More significantly, satellite altimeter data from NASA's ICESat and ESA's Envisat, with comprehensive coverage of the Arctic Ocean to 86°N and 81°N respectively, analyzed by STAR scientists and their colleagues, show a robust, basin-scale thinning of sea ice since 2003. Climate modelers suggest that predicted Arctic amplification i.e., pronounced increases in lower atmosphere air temperatures over the Arctic, may already have begun in association with the decline in sea ice extent – and thickness — during the past decade.

Change in Arctic Sea Ice above the Water Level



Sea ice freeboard (height of ice above the water level) in 2003 and 2008, where freeboard is a proxy for total ice thickness.
Note the increased amount of thinner ice (bluer areas) in 2008. Although the ICESat mission has come to an end, altimetric remote sensing of sea ice thickness has a bright future. NASA plans to launch a second laser altimeter satellite, ICESat-II, about five years from now.

Coral bleaching in action

Mass coral bleaching is caused by unusually high water temperatures that stress corals. Coral polyps expel the symbiotic microalgae living in their tissues, exposing the white skeleton underneath. Corals typically recover from mild bleaching and gradually regain their color by repopulating algae. However, severe or prolonged bleaching can kill all or part of the coral. The photo below shows the substantial bleaching of both the coral colony and the clam living within it, indicating that many reef organisms are susceptible to bleaching. Also note the green macroalgae that have overgrown dead portions of the coral. Algal overgrowth hinders the coral colony's recovery and can shift reef community structure from a dominance by corals to a dominance by algae. Climate change is already causing bleaching, disease, and death of corals.

This image was taken by Dr. C. Mark Eakin (NOAA Coral Reef Watch Coordinator) off the coast of Phuket, Thailand on June 22, 2010.

Coral Bleaching

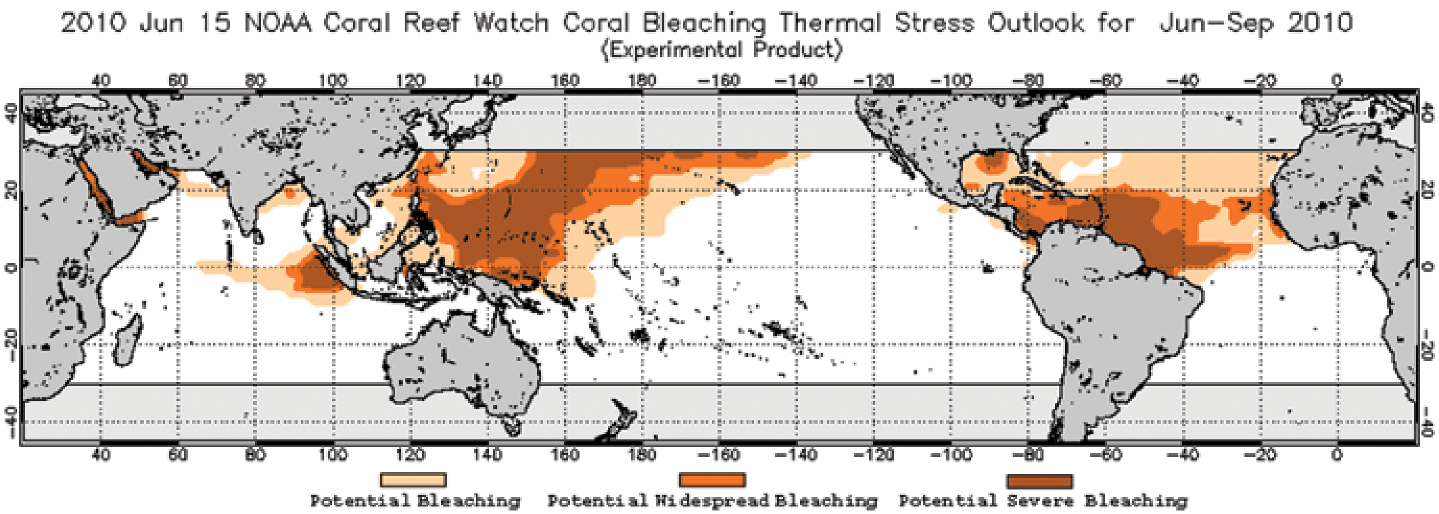
C. Mark Eakin, Jacqueline Rauenzahn, Gang Liu, Tim Burgess, Tyler Christensen, Scott Heron, Jianke Li, Ethan Lucas, Jessica Morgan, Britt Parker, William Skirving, and Alan Strong

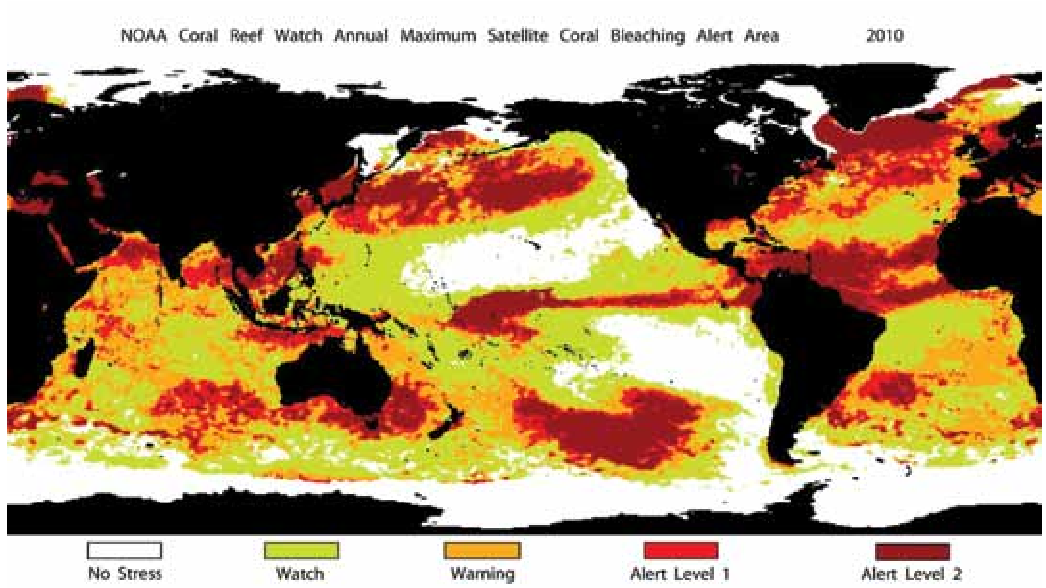
Coral reefs are among the most diverse and valuable ecosystems on Earth. They provide humans with hundreds of billion dollars in economic and environmental services such as food, coastal protection, and tourism. Serious threats, including climate change, unsustainable fishing, and land-based pollution, impact coral health and contribute to coral bleaching, reduced growth, infectious diseases, and coral death. Approximately half of the coral reef ecosystem resources currently monitored is considered to be in 'poor' or 'fair' condition. The world has lost 19% of its original coral reef area; 15% is seriously threatened with loss within 10–20 years; and 20% is under threat of loss in 20–40 years.

NOAA Coral Reef Watch (CRW), initiated and implemented by STAR, has developed and delivers a suite of products based on satellite observations to provide information to managers and researchers on environmental stresses to coral reef ecosystems. CRW's operational sea surface temperature (SST)-based products are the world benchmark for predicting coral bleaching (sidebar). This global system uses near-real-time data from NOAA satellites to monitor coral bleaching thermal stress and issue alerts. Developed by STAR, key products, which are currently delivered at a 50-km resolution and are updated twice-weekly, include SST, SST Anomaly, Coral Bleaching HotSpots, Degree Heating Weeks, Bleaching Alert Areas, Short-Term SST Trends, and a free, automated bleaching alert e-mail system that alerts subscribers when conditions can cause bleaching.

CRW is collaborating with numerous domestic and international partners to develop new products with higher spatial and temporal resolutions based on NOAA's next generation satellite SST products and using additional environmental parameters.

Predicting and Monitoring Coral Bleaching





TOP: CRW's Seasonal Bleaching Thermal Stress Outlook, an experimental product based on climate forecast models, provided advance warning of bleaching conditions. Map shows the 4-month cumulative thermal stress potential prediction for June-September 2010.

BOTTOM: CRW's Bleaching Alert Area product indicates areas where thermal stress has currently reached levels that can cause bleaching. In 2010, major bleaching occurred throughout parts of the Indian Ocean, Southeast Asia (the Coral Triangle), the central Pacific, and the Caribbean. CRW was able to provide coral reef managers and scientists with nowcasts of current bleaching environmental conditions as the event unfolded. (Map shows a composite of the thermal stress for all of 2010).

Temperature and vegetation

Satellite observations as well as ground based observations have shown that warming of the climate is unequivocal. Global surface temperature has increased approximately 0.2°C per decade in the last 30 years. Temperature affects the growth and productivity of plants since rates of photosynthesis rise with increasing temperatures. A gradual increase in temperature in a region can translate into increasing vegetation growth, lengthening of the growing season, and early greening and flowering of the vegetation. But with large increases in temperature, photosynthesis rates reach a peak and then start to decline. These conditions may cause vegetation stress, leading to decreased plant growth and lower crop yields. Extreme increases in temperature may even cause desertification. Changes in precipitation rates and the beneficial effect of increasing CO_2 levels on plant growth may either mitigate or reinforce any temperature effects on vegetation.

Changes in vegetation can feedback on the temperature. For example, increased vegetation can lead to greater evaporation of water from plants – a cooling effect – and lower reflection of solar radiation – a warming effect.

Vegetation and Surface Temperature Trends

Marco Vargas, Felix Kogan, and Wei Guo

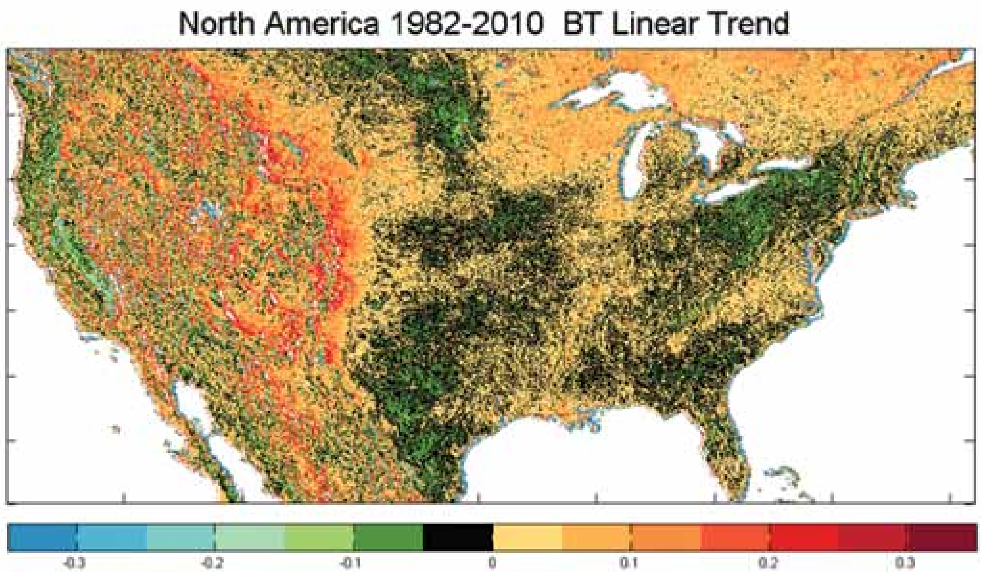
A 30-year record of reflected and emitted electromagnetic radiation from the Earth's surface and atmosphere has been accumulated from the Advanced Very High Resolution Radiometer (AVHRR) instruments onboard NOAA polar orbiting satellites. This long-term satellite record allows us to do land surface monitoring and prediction.

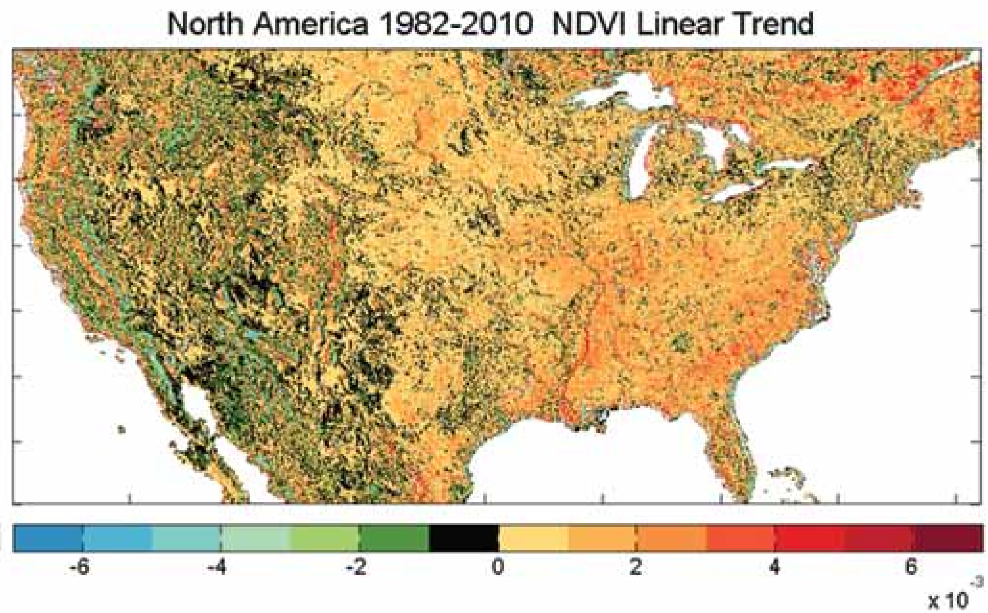
Satellite observations from AVHRR are used to derive the Normalized Difference Vegetation Index (NDVI) – an index of the coverage and vigor of vegetation – and infrared Brightness temperature (BT) – an approximate measure of the surface temperature.

Warming of the climate due to human and natural drivers has been confirmed from satellite and in-situ observations. Increases in near surface air temperatures could affect surface vegetation and vice versa (see sidebar).

The figure (opposite page) shows linear trends of NDVI and BT over the last three decades for each 4 km pixel in the USA, part of Mexico, and Canada. From time series such as these, STAR scientists are studying long term vegetation trends and their causes. The issue is complex. Surface temperature is not the only variable affecting vegetation: changing precipitation and CO_2 are also important factors.

Surface Infrared Temperature and Vegetation Trends: 1982-2010





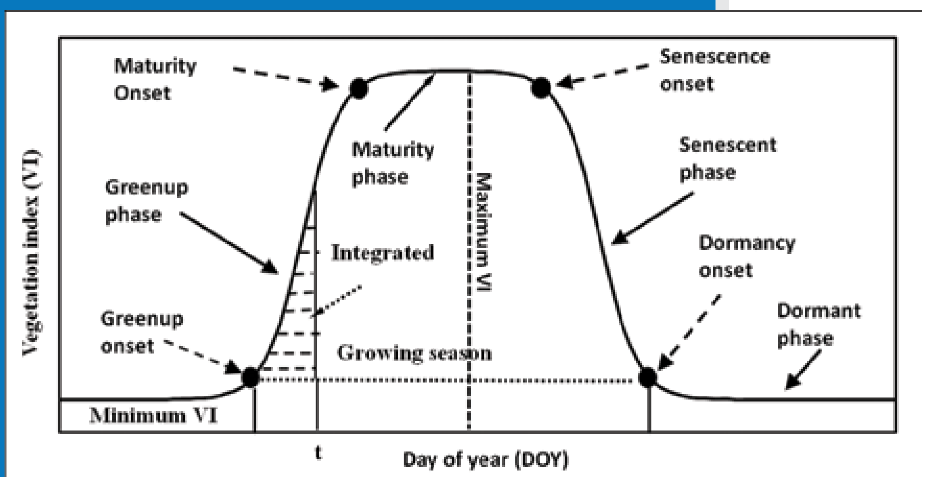
Surface infrared brightness temperature trend (BT: °C/3 decades) – a measure of the surface temperature trend – and the vegetation (Normalized Difference Vegetation Index) trend (NDVI/3 decades) for the last three decades over North America. Vegetation (right panel) shows a positive trend in the central and eastern regions. Surface temperature (left panel) shows a mostly positive trend in the western region and a combination of positive and negative trends in the central and eastern states. Basically, as the brightness temperature increased in the western U.S., vegetation vigor has decreased in the same region. Conversely, as the brightness temperature in the eastern U.S. has decreased, the vegetation vigor in the same region has increased.

Spring flowers and fall colors

Vegetation phenologic metrics – the timing of important events in the seasonal cycle of vegetation – can be detected from the satellite-based measure of vegetation amount and health, the Normalized Difference Vegetation Index (NDVI). The four phases of the seasonal cycle of NDVI are characterized by four phenologic transition dates: the onset of greenup (leaf-out), plant maturity, senescence (plant aging), and dormancy.

The NDVI time series also reveals the growing season length. During the fall senescent phase of deciduous plants, foliage coloration occurrence (low coloration, moderate coloration, near peak coloration, peak coloration, and post peak coloration) can be retrieved from an NDVI related index – a brownness index.

Shifts in the phenologic metrics can be traced to climate change and human activity.



Satellite Vegetation Phenology

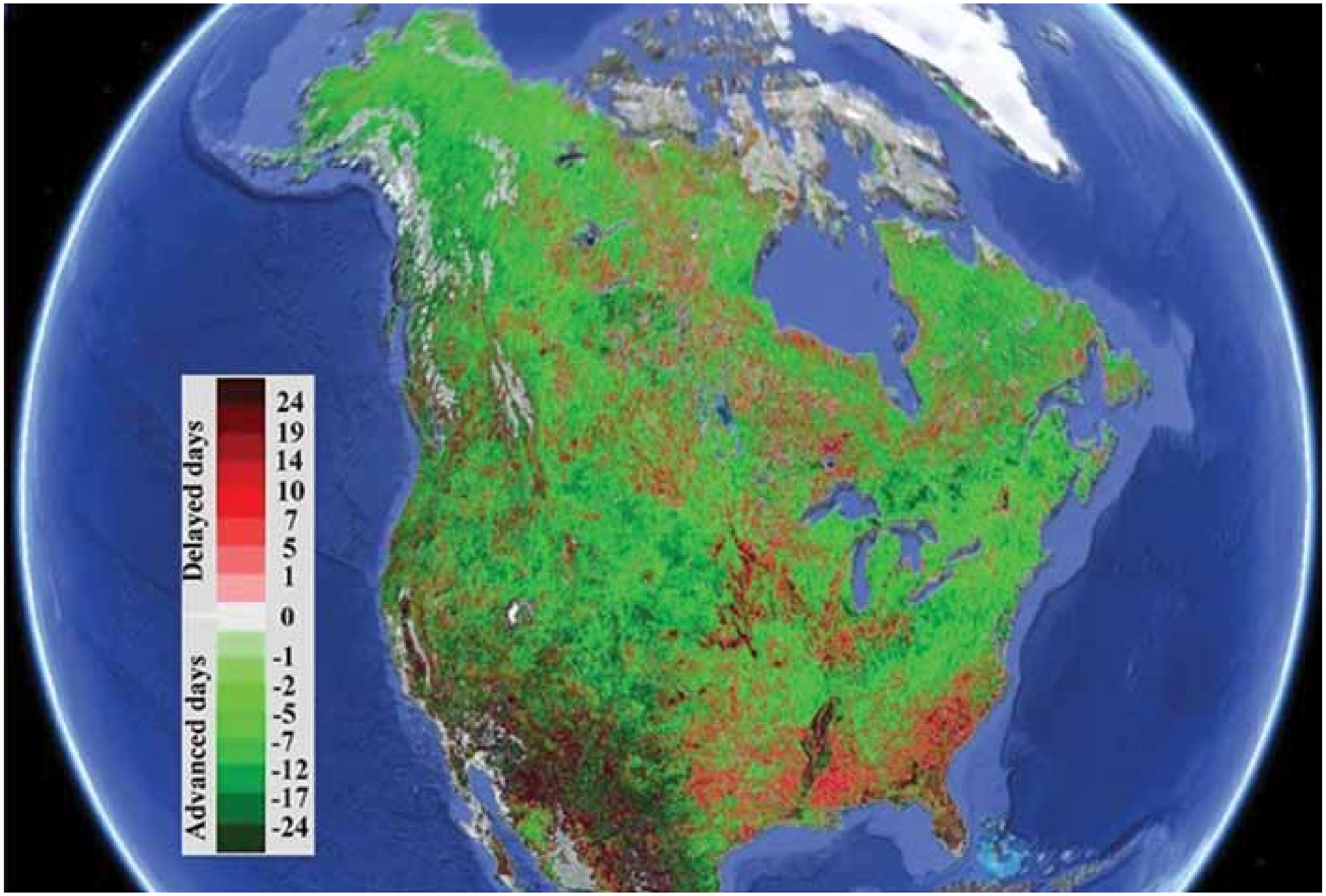
Xiaoyang Zhang, Mitchell D. Goldberg, and Yunyue Yu

Vegetation phenology is the study of recurring events in a plant's life cycle – the greening of vegetation in the spring, for example – and how these are influenced by seasonal and interannual variations in climate. The seasonal vegetation cycle is obviously due to the annual climatic cycle, and shifts in phenology over the long term are sensitive indicators of climate change.

Real-time phenologic monitoring enables foresters and farmers to manage crops and forests, health officials to determine allergenic pollen occurrences and disease outbreaks, and weather modelers to quantify land-surface physical properties. STAR scientists have developed a tool to reconstruct long-term phenology records and to monitor real-time vegetation phenologic events from satellite data. This tool identifies the timing and rates of vegetation growth seasonally and inter-annually by analyzing the variation of vegetation phenology with time based on the Normalized Difference Vegetation Index (NDVI) – a measure of vegetation abundance and health – from the observations of the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA's polar satellites. This dataset has been used to generate long-term phenologic metrics and their trends over a 30 year period. A major advantage of the technique is that since each year's analysis is based only on the phenology cycle that year, it is insensitive to unknown drifts in instrument calibration.

The research suggests that global warming may be causing an earlier spring bloom in most of North America, but in some mid-low latitude regions, warming may actually be leading to delayed plant budburst and seed sprout.

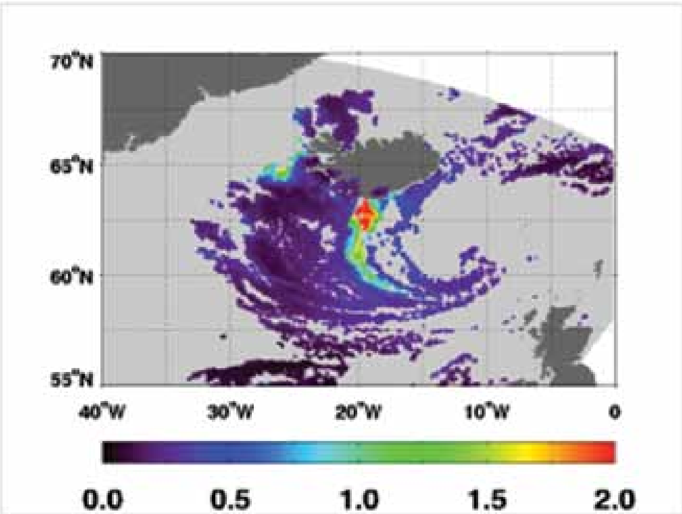
Earlier Greening



Long-term trend of vegetation greenup onset (plant budburst) is detected from weekly satellite vegetation index (1981-2005) at a spatial resolution of 4 km across North America. The trend reveals that spring greenup has been accelerated by an average of 8 days in cold and temperate climate regions. In warmer subtropical regions, however, vegetation greenup onset varies progressively from an earlier (north) to later (south) date because the number of winter chilling days is insufficient to fulfill vegetation chilling requirements.

Volcanic dust and sunlight

One of the primary effects of volcanic aerosols is to decrease the amount of solar radiation reaching the surface. Thus major volcanic eruptions lead to a cooling at the surface.



The image shows the aerosol optical thickness – the total amount of dust in a vertical column of atmosphere – around Iceland immediately following the eruption of the Eyjafjallajökull Volcano. (Dark gray area is land; light gray and white areas are not observed mostly due to cloud cover.) Elevated aerosols (warm colors) are clearly seen in the plume. Radiative transfer models predict a decrease by over 30% in the solar radiation available for heating the surface under the plume.

Aerosols, Volcanoes and Climate

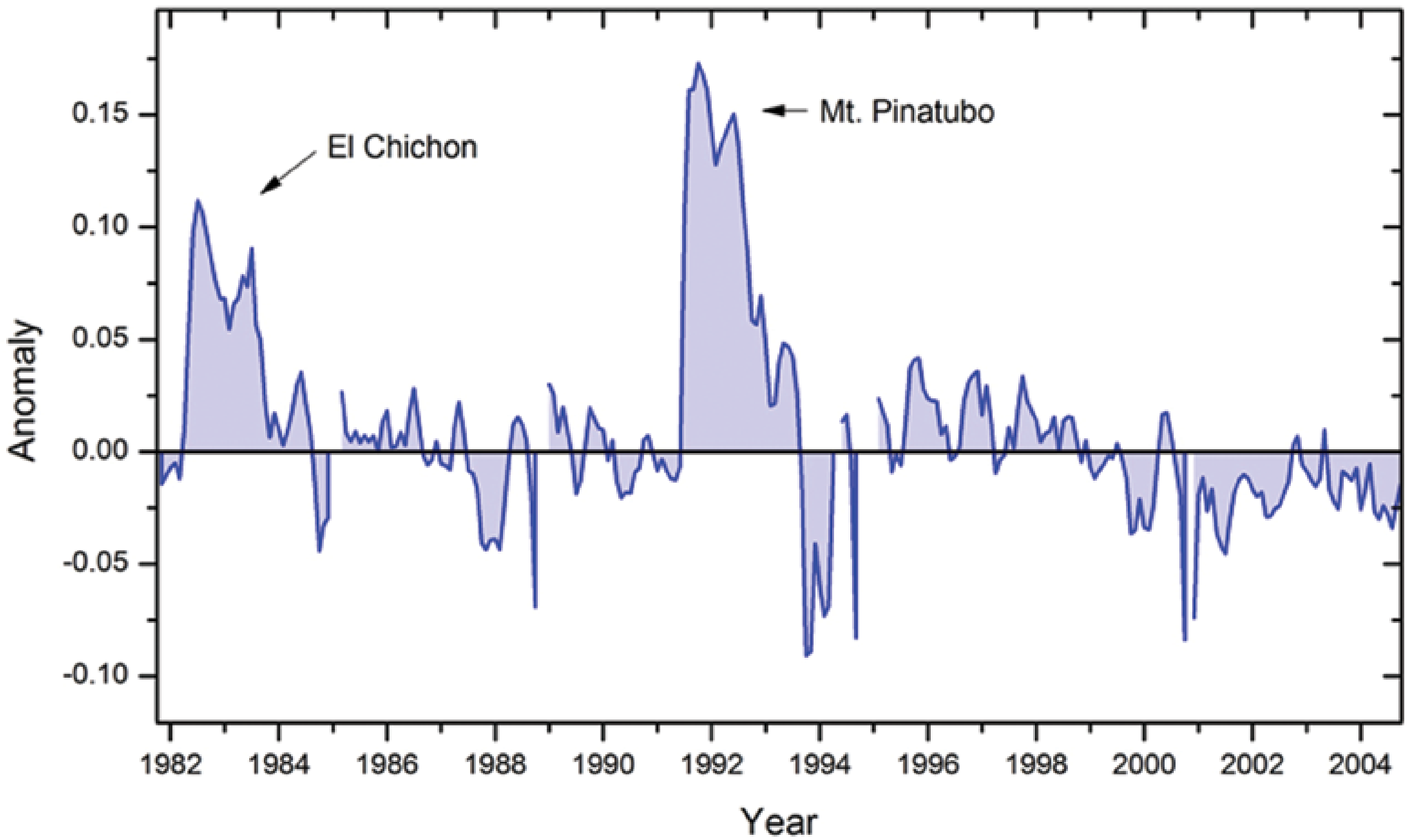
Istvan Laszlo

Solid and/or liquid particles, called aerosols, are inherent constituents of the atmosphere. They are often seen as haze, smoke, and dust. Aerosols exhibit an immense range of diversity in size, composition, origin, and temporal and spatial distributions. Sizes range by a factor of 10,000 – from a few nanometers (10^{-9} meters) to a few tens of micrometers (10^{-6} meters). Depending on the type, and the source, aerosols remain in the atmosphere for less than a day to several years.

Aerosols are produced by both natural processes – smoke from forest fires, windblown Saharan sands – and as a result of human activities – biomass burning, for example. The latter currently amounts to about 10% of the global aerosol mass. Strong volcanic eruptions inject gases and particles into the stratosphere, where they spread over most of the globe, remaining for years before they eventually fall out. Because they reflect solar radiation back to space, their presence leads to a cooling of the Earth, reducing global surface temperatures by about 1 deg C and counteracting greenhouse warming for the year or two before they fall out.

Satellites are increasingly used for measuring the amount of aerosols present in the atmosphere. This can be done because the intensity and spectral distribution, or "color", of solar radiation reflected back to space by aerosols depend on their amount, size, shape and type. STAR scientists use the measurements of the Advanced Very High Resolution Radiometer onboard the NOAA satellites to study the changes in aerosol amount over the global oceans.

Aerosol over Oceans



The graph shows the variation with time in the amount of aerosol as represented by the aerosol optical thickness (AOT) over the global oceans. The departure of monthly AOT values from their multi-year mean value (anomaly) is plotted. The AOT was determined from the Advanced Very High Resolution (AVHRR) instrument flown onboard operational polar orbiting NOAA satellites. The pattern is characterized by seasonal fluctuations in AOT and by two maxima corresponding to the eruptions of El Chichon in April 1982 and Mount Pinatubo in June 1991. Following these volcanic eruptions the aerosol optical thickness increased by 0.1-0.15 globally. This is more than double of the typical amount in years without major volcanic events. There is also a hint of a gradual decrease in AOT after about 1996. The question of whether this decrease is real or not is an active area of research.

Arctic Climate Interactions

Jeff Key

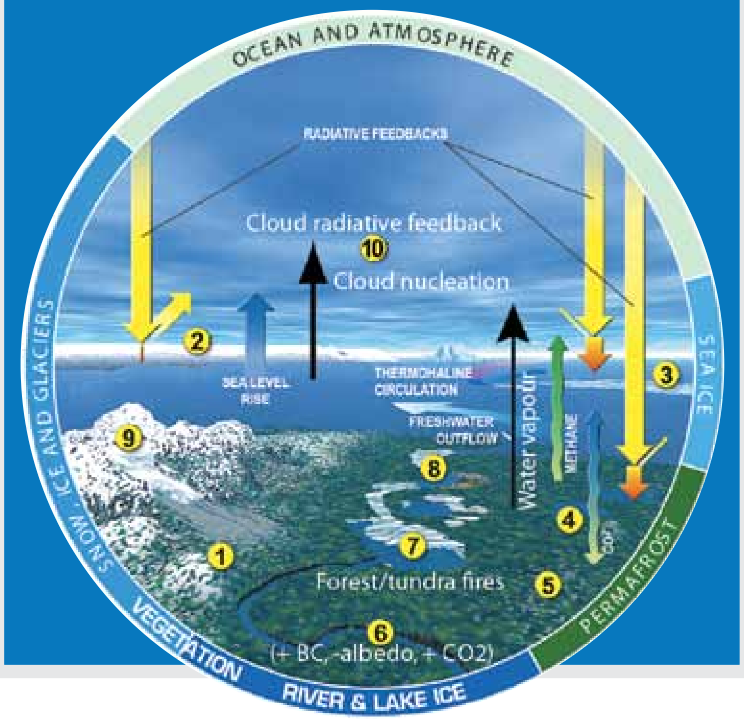
The Arctic has experienced dramatic changes over the past few decades. Surface temperature, a fundamental indicator of climate change, has increased significantly. The average extent of summer sea ice cover is declining at a rate that would leave most of the Arctic ice-free in summer by mid-century or earlier. Snow cover has decreased, permafrost temperatures have increased, and ice sheets have declined.

Satellites can be used to measure most characteristics of Arctic climate, but no single sensor is sufficient. Passive microwave, radar, lidar, gravity, visible, and thermal sensors are all needed to observe changes in sea ice cover, motion, and thickness, snow extent and water content, ice sheet thickness, atmospheric temperature and humidity, winds, cloud properties, and sea level.

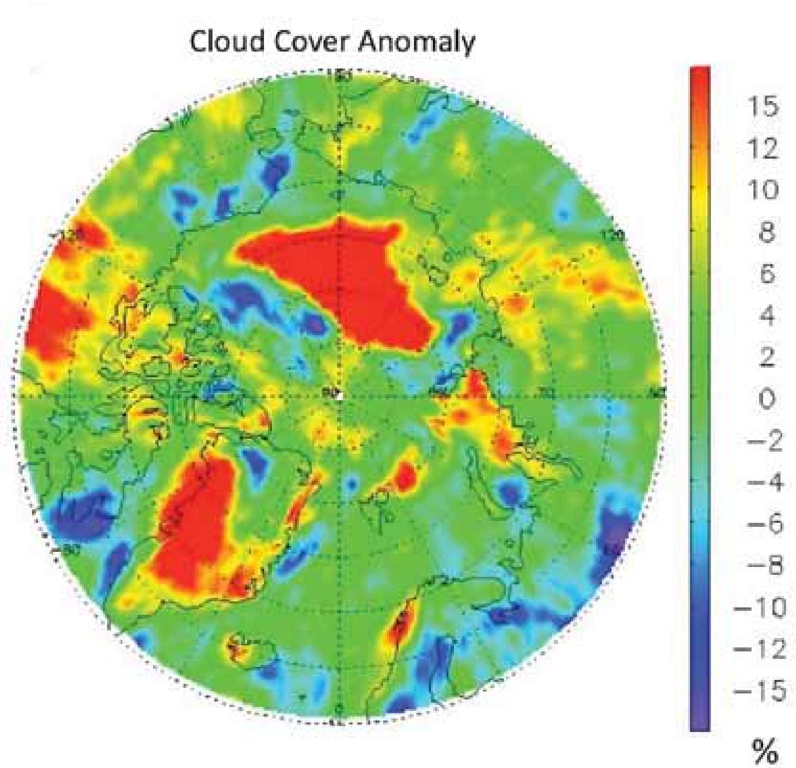
Satellite climate data records are becoming increasingly important in the analysis of interactions between climate components and in quantifying feedbacks – amplifications or reductions of an initial climate change. STAR scientists have investigated the influence of trends in sea ice and cloud cover on trends in surface temperature over the Arctic Ocean. The study showed that changes in sea ice account for most of the local summertime warming, while trends in winter cloud cover account for most of the cooling in the central Arctic. Of course, large-scale changes in temperature are the primary cause for the decline in sea ice, but this study quantified the smaller-scale feedbacks. The interactions are complex but revealing: if cloud cover had not changed the way it did, the Arctic might have warmed even more than what we have observed.

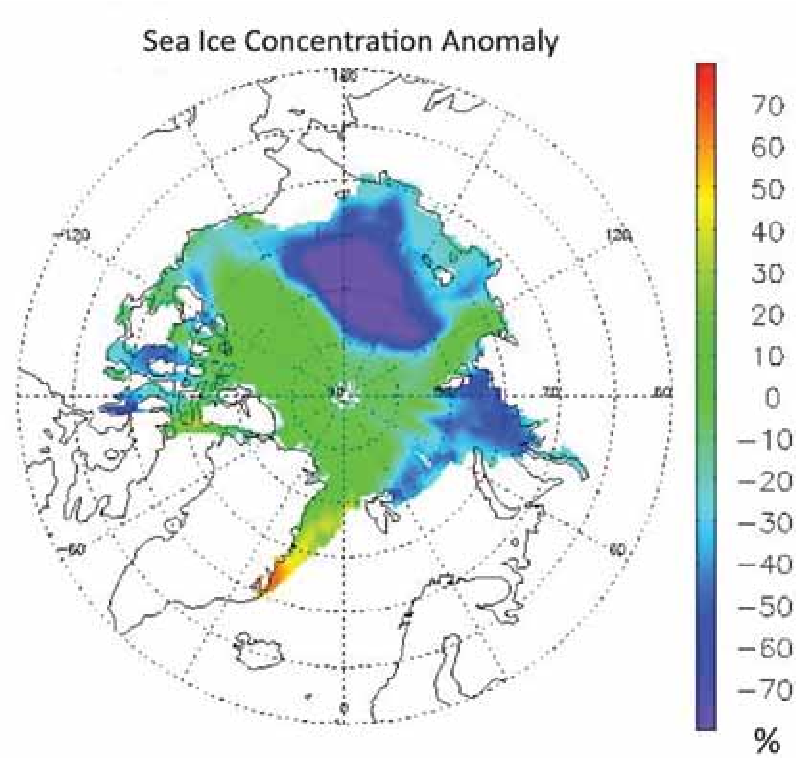
Arctic climate feedbacks and processes

There are many complex interactions in the Arctic climate system: (1) Melting snow increases solar radiation absorption over land. (2) Ice sheet melting contributes to sea level rise. (3) Retreating sea ice increases ocean absorption of solar radiation and ocean to atmosphere transfer of heat and moisture. (4-6) Degrading permafrost increases methane – a greenhouse gas – emission; wetland drying increases CO_2 emission. (6-8) Increasing precipitation plus melting snow change the freshwater outflow. Shrinking lake ice cover and runoff have ecological impacts. (9) Retreating glaciers increase runoff. (10) Changes in cloudiness impact the radiative energy budget. (Photo credit: Prowse, T.D., 2009. Introduction: hydrologic effects of a shrinking cryosphere, Hydrol. Process., 23, 1-6, doi: 10.1002/hyp.7215.)



Changes in Sea Ice and Cloud Cover are Related





A decrease in sea ice cover results in greater evaporation from the surface, a more unstable lower atmospheric layer, and an increase in cloud amount. This was particularly obvious during the summer of 2007, which saw a record minimum in Arctic ice cover in the satellite era. Left: Cloud amount anomalies (departures from normal) from Moderate Resolution Imaging Spectroradiometer (MODIS) observations over the Arctic for September-October 2007 relative to the 2002-2007 mean. Right: Sea ice concentration anomalies from Advanced Microwave Scanning Radiometer from EOS (AMSR-E) observations for the same period. Large anomalies in ice cover correspond to anomalies in cloud cover.

Reconstruction of historical oceanic precipitation variations

The map on the opposite page shows the global distribution of 20th century precipitation trends derived from the climate reconstruction method. The trends tend to be largest over tropical oceans, where satellite-based analyses indicate that precipitation variations are also largest. Patterns in the map indicate relationships between oceanic and land trends over the century.

Although there are both positive and negative trends in the map, the time series (lower panel) indicates that over the course of the 20th century, average monthly precipitation over the global ocean has increased by about 1 mm. The preliminary uncertainty estimates for this change is ±0.6 mm. The 3 to 10 year variations are much larger than the multi-decadal variations, so a long time series such as this is needed to evaluate trends. For the shorter satellite period, the satellite-based analysis shows variations consistent with the reconstructed data, lending credibility to the use of the method for historical reconstruction.

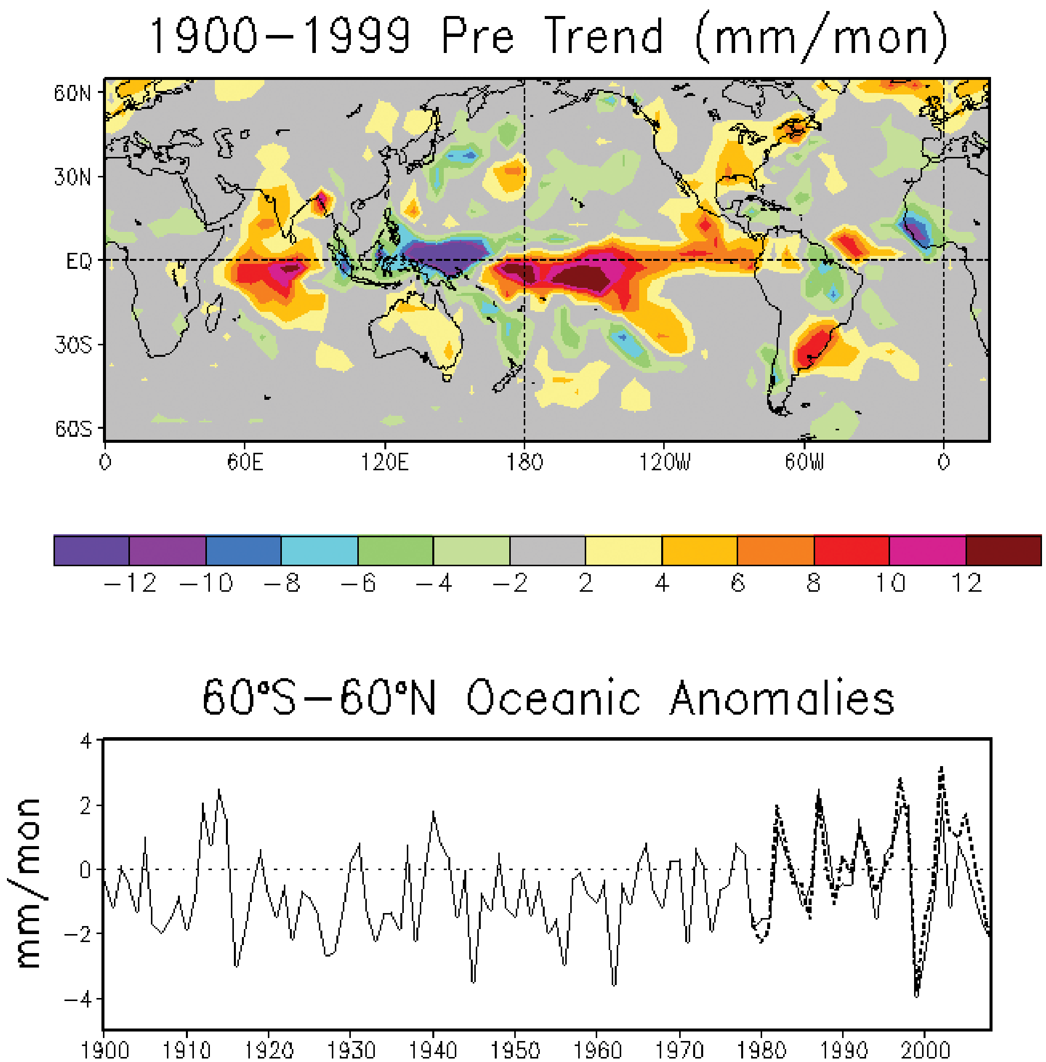
Climate Reconstructions

Thomas M. Smith and Phillip A. Arkin

Today, global sampling of climate variables is nearly complete using satellite-based data, which became available around 1980. Prior to that time, global coverage was limited, with observations concentrated in populated areas and along the major ocean routes. In order to study long-period climate variations we would like to have more complete analyses for the pre-satellite period. Climate reconstructions are analyses that have been developed to fill the many gaps in the pre-satellite period. Reconstructions exploit correlations between the available data and the data gaps. The satellite data from the modern period are used to develop those correlations, which are then applied to the sparse historical data to fill in the gaps. Because of the sparseness of the historical data, reconstructions typically only resolve large scale variations on monthly or longer time scales.

STAR scientists and their collaborators have recently reconstructed an important climate field: global precipitation. Over most land regions, rain gauge data are available since 1900. Over oceans, prior to 1979, measurements of precipitation were few and far between, so reconstructions are needed to produce time series of historical global variations. A blend of satellite and gauge products – the Global Precipitation Climatology Project (GPCP), which began in 1979 – provides the high-quality global data needed to establish the statistical connections between land plus island gauge data and global ocean precipitation patterns. These relationships are applied to the historical land and island rain observations to generate a time series of global precipitation anomalies (departures from normal).

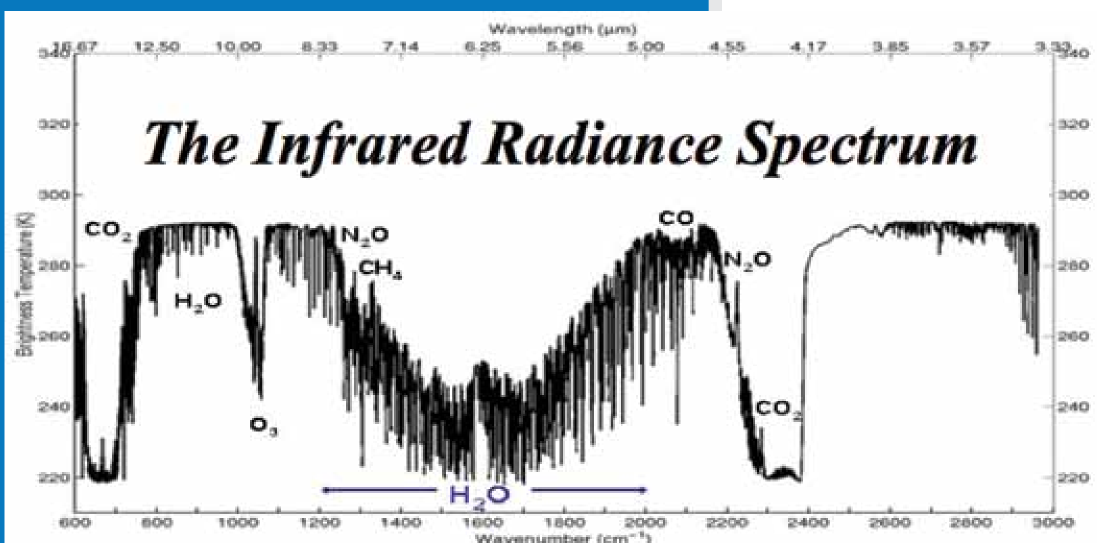
20th Century Precipitation Trend



Near-global precipitation variations. The geographical distribution of precipitation trends for the 20th century reconstruction is shown in the upper panel. The annual 60°S-60°N average over ocean areas is shown in the lower panel for the reconstruction and for the satellite-based analysis (heavy dashed line). Over the 20th century, average monthly precipitation over the ocean has increased by about 1 mm.

Hyperspectral infrared spectrum

Spectrally resolved (very high spectral resolution) infrared radiances provide the opportunity not only to detect climate change but also to understand the processes contributing to the change. Do these processes involve changes in clouds, temperature, water vapor, carbon compounds, ozone, etc? Since different parts of the spectrum (see example below of Earth's emission spectrum) are sensitive to different gases, layers of the atmosphere, and cloud properties, observations of spectrally resolved radiance permit dissecting and understanding the root causes of the observed climate changes. Also, spectrally resolved radiances can be used to validate weather and climate models, by simply comparing the observed spectra with those calculated from the model's geophysical parameters. (Photo credit: University of Wisconsin)



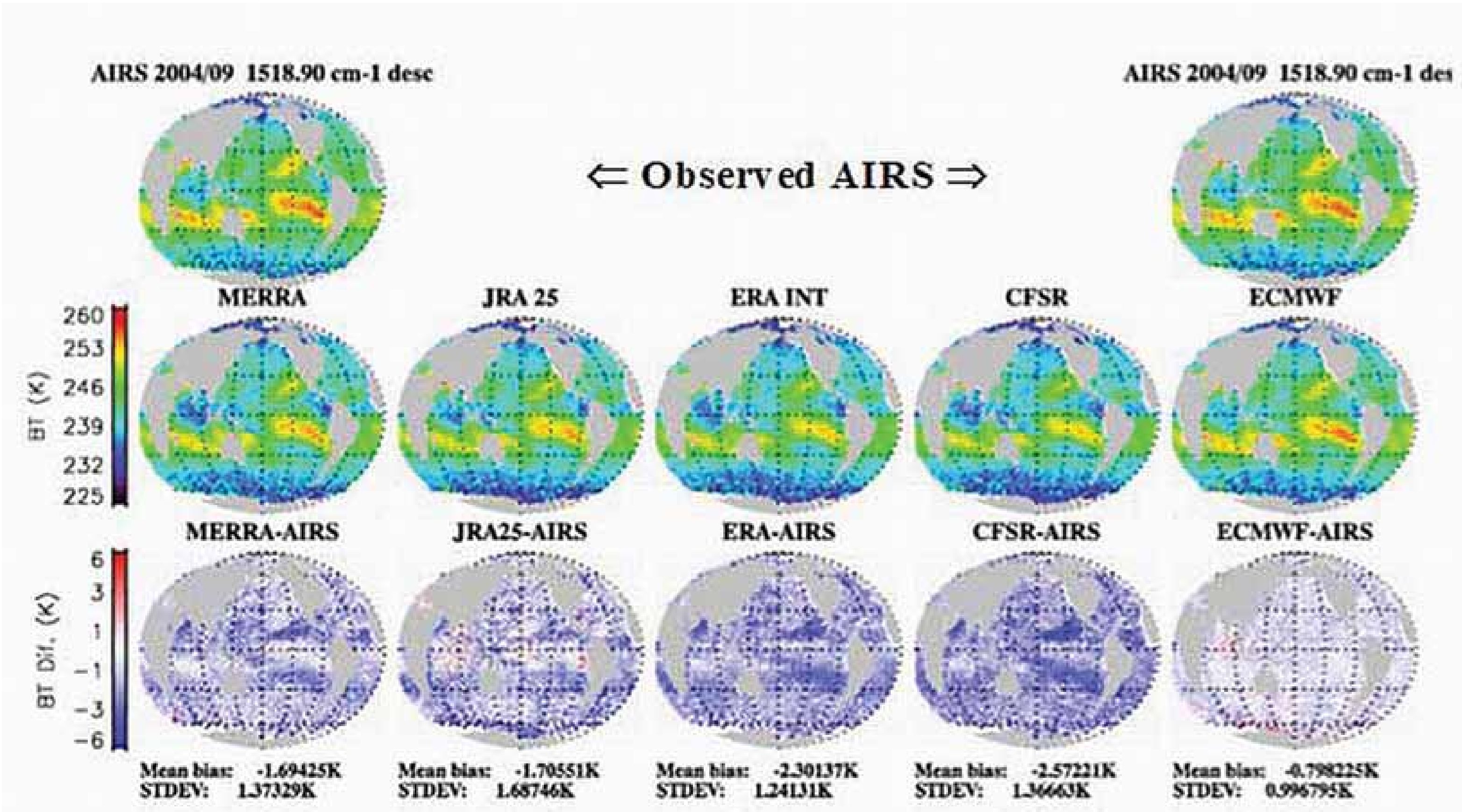
Checking Climate Reanalyses

Mitchell Goldberg and Likun Wang

There is a growing consensus that increasing industrial emissions of greenhouse gases over the past 150 years are causing warming of the atmosphere and oceans, rising sea levels, melting ice caps and glaciers, more frequent severe weather, and regional shifts in precipitation patterns. To enable policy makers to make informed decisions on decreasing future emissions and mitigating and adapting to greenhouse warming, it is important to observe, document, understand and predict climate change.

A powerful tool for constructing a record of the climate is a climate reanalysis system. Similar to a numerical weather prediction (NWP) analysis system, it assimilates data from numerous observing systems. It is run on a daily basis for many decades to provide a historical description of the atmosphere. However, large differences exist between datasets generated by different groups, most likely due to varying NWP model physics and data assimilation techniques. Accurate independent measurements are needed to check the reanalyses. Fortunately, over the past decade, a new generation of extremely accurate hyperspectral (observations at thousands of wavelengths) infrared instruments – NASA's Atmospheric InfraRed Sounder (AIRS) and the European Infrared Atmospheric Sounding Interferometer (IASI) – has been launched into space. Direct comparisons between observations from these two instruments show absolute differences well within 0.1 °C, making them reliable space-based standards for verifying reanalyses, as well as climate prediction models. An example of applying the technique is shown in the figure on the opposite page.

Differences between Model Simulations and Satellite Observations



The Atmospheric InfraRed Sounder (AIRS) channel with a frequency of 1519.90 wavenumbers (cm-1) is very sensitive to upper tropospheric water vapor. The observed AIRS data are compared with simulated AIRS measurements computed from four different climate reanalyses of atmospheric states (NASA (MERRA), Japan (JRA), ECMWF (ERA), NCEP (CFSR)), and one weather analysis (ECMWF). Upper panel: AIRS brightness temperature (BT) – approximate temperature of the emitting atmospheric layer – observations; Middle panel: Simulated AIRS BT observations; Lower panel: Difference in BT between observed and simulated AIRS observations. A variation in upper tropospheric water vapor of about 10% results in a BT change of about 1 deg K. The ECMWF weather analysis has the best agreement with AIRS and there is high confidence that its upper tropospheric water vapor field is the most accurate. The high accuracy of hyperspectral infrared radiances provides a very powerful tool for validating and improving critical data for assessing and predicting climate change.

El Niño Southern Oscillation (ENSO) impacts fishing

Fishermen along the coasts of Peru and Ecuador have been affected by the El Niño phenomenon for centuries. The key element of the El Niño is the interaction between the sea surface and winds. When the winds are from the southeast, the water piles up in the western Pacific causing broad ocean warming and upwelling (deep, colder water rising to the surface) along the South American coast. This event brings nutrients to the surface for the fishery food chain and fisheries thrive. When the wind decreases, the upwelling declines and so do the fish. Every few years, fish in these coastal waters virtually vanish causing a disruption in the fishing industry and regional economic woes.

However, other areas may benefit. The El Niño event off the coast of Ecuador forces the mass migration of marine life away from the equator in search of food and survivable water temperatures. As a result, albacore have been found as far north as Oregon, and marlin have been caught outside the Golden Gate Bridge area, which is far from their traditional habitat.

Left: Marlin (Photo Credit: NOAA Fisheries/Ken Neill); Right: Albacore (Photo Credit: NOAA Fisheries).

Abrupt Climate Change

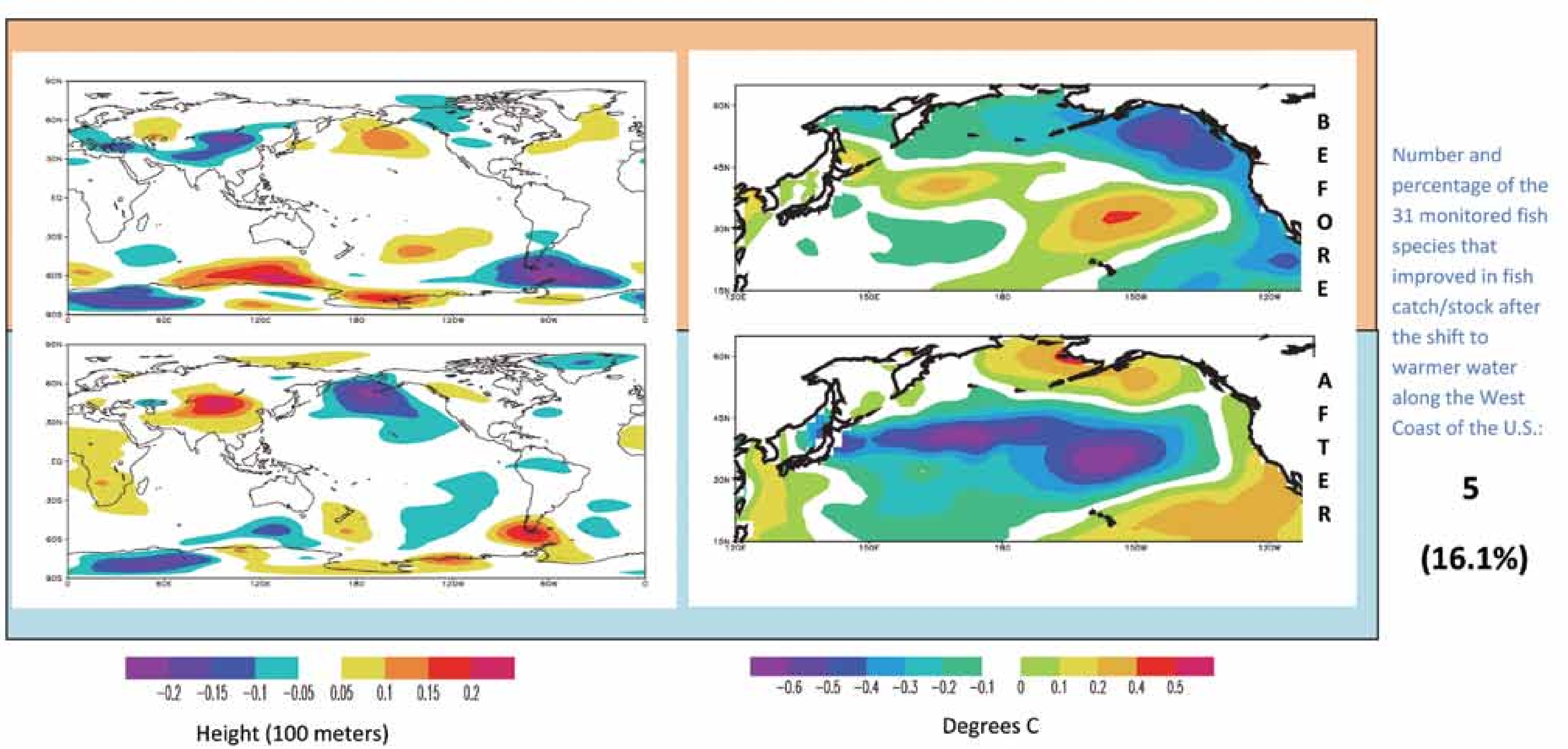
Alfred M. Powell, Jr. and Jianjun Xu

Abrupt climate change has been defined by the U.S. Climate Change Science Program as a large-scale change in the climate system that takes place over a few decades or less, persists, and causes substantial disruptions in human and natural systems. When satellite data are merged into a time series of global atmospheric or ocean conditions with other historical observations, they provide the tools to study environmental changes such as abrupt climate shifts.

The polar atmospheric wave pattern circles the globe and determines regional weather and climate patterns. When the polar wave pattern varies, the winds around the globe change. The surface wind drives the ocean currents and can cause the sea surface temperature (SST) to change. An abrupt climate shift occurred in 1977-78 and the decadal state before and after the shift are very different. The figure (opposite page) shows the differences in the atmospheric wave pattern and its impact on the sea surface temperature. The atmosphere before the shift shows a clockwise high pressure (yellow) system in the Gulf of Alaska which advects cold water southward along the U.S. Pacific coast. After the shift, a counter-clockwise low pressure system (blue) advects water northward along the U.S. West coast. For the 1977 climate shift, the eastern Pacific SST was colder before the shift and warmer after it. The pre- and post-shift patterns in the atmosphere and the sea surface are essentially inverses of each other. The change from cold pre-shift temperatures to warm post-shift temperatures affected 5 of the 31 monitored fish species caught off the California coast resulting in a 16 percent change in the ecosystem.

Environmental changes such as this one can have significant impacts on our nation's food supply with major regional consequences. Similar impacts are also associated with events such as El Niño (see sidebar).

Synchronous Abrupt Changes in the Atmosphere, Ocean and Ecosystem



The figures show the 1977-78 abrupt climate shift in the atmosphere and the ocean. The top two charts show the decade prior to the shift, and the lower two charts show the decade after the abrupt climate shift. The global atmospheric change is shown in the surface pressure pattern as indicated by the height of the 1000 hPa pressure surface (left two charts). The pressure pattern indicates the wind direction and surface stress before and after the regime shift. The changes in the winds produced the sea surface temperature differences (right two charts) in the eastern and central Pacific. A cold SST anomaly (departure from normal) can be seen before the shift and a warm SST anomaly can be seen after the shift in the eastern Pacific along the U.S. west coast. The normalized fish catch/stock amounts for the 31 fish species monitored along the California coast are used to indicate ecosystem change. Five (5) of the 31 fish species monitored were identified with greater catch/stock amounts when the sea temperature warmed after the shift. This is a 16% change in the ecosystem fish catch which could have significant economic impacts.

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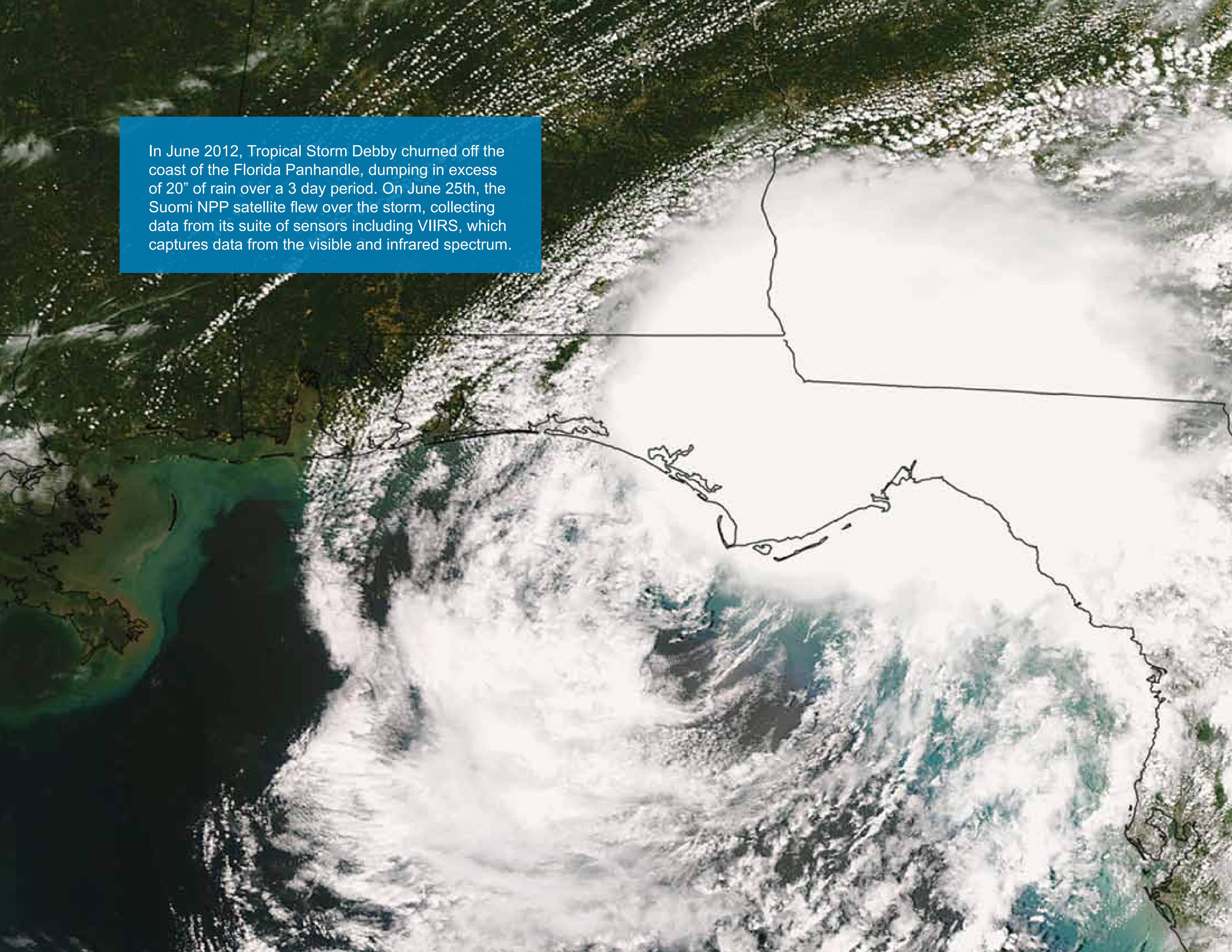
List of Acronyms and Abbreviations

A-Train	Series of Earth observation satellites, one following the other in polar orbit
ABI	Advanced Baseline Imager
ACSPO	Advanced Clear-Sky Processor for Oceans
AIRS	Atmospheric Infrared Sounder
AMSR-E	Advanced Microwave Scanning Radiometer from EOS
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
AQI	Air Quality Index
ATMS	Advanced Technology Microwave Sounder
ATOVS	Advanced TIROS Operational Vertical Sounder
AVHRR	Advanced Very High Resolution Radiometer
AWIPS	Advanced Weather Interactive Processing System
BT	Brightness Temperature
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
CFCs	Chlorofluorocarbons
CFSR	Climate Forecast System Reanalysis
CGMS	Coordination Group for Meteorological Satellites
CNES	Centre National d'Etudes Spatiales (France)
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CrIS	Cross-track Infrared Sounder
CRTM	Community Radiative Transfer Model
CRW	Coral Reef Watch
CZCS	Coastal Zone Color Scanner
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
DPI	Derived Product Imagery
ECMWF	European Centre for Medium-Range Weather Forecasts
EF	Enhanced Fujita
ENVISAT	Environmental Satellite
EOS	Earth Observing Satellite
EPA	Environmental Protection Agency
ESA	European Space Agency
ESI	Evaporative Stress Index
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FY-2	Chinese geostationary meteorological satellite
FY-3	Chinese polar orbiting meteorological satellite
GEBCO	General Bathymetric Charts of the Ocean
GEO	Geostationary satellite
GHG	Greenhouse gases
GMAO	Global Modeling and Assimilation Office

GOES	Geostationary Orbiting Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GPCP	Global Precipitation Climatology Project
GPS	Global Positioning System
GPS/RO	Global Positioning System/Radio Occultation
GRACE	Gravity Recovery and Climate Experiment
GSICS	Global Space-based Inter-Calibration System
GVH	Global Vegetation Health
HAB	Harmful Algal Bloom
HIRS	High-resolution Infrared Radiation Sounder
IASI	Infrared Atmospheric Sounding Interferometer
IBCAO	International Bathymetric Chart of the Arctic Ocean
ICESat	Ice, Cloud, and land Elevation Satellite
IHO	International Hydrographic Organization
Insat	Indian National Satellite
IOC	Intergovernmental Oceanographic Commission
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
Jason	Ocean altimetry satellite
JCSDA	Joint Center for Satellite Data Assimilation
JPSS	Joint Polar Satellite System
JRA-25	Japanese 25-year Reanalysis
LEO	Low Earth orbiting satellite
LI	Lifted Index
LST	Land Surface Temperature
MABL	Marine Atmospheric Boundary Layer
MERIS	Medium Resolution Imaging Spectrometer
MERRA	Modern-Era Retrospective Analysis for Research and Applications
METEOR	Russian LEO weather satellite
Meteosat	European geostationary meteorological satellite
MetOp	Meteorological Operational satellite program
MHS	Microwave Humidity Sounder
MIRS	Microwave Integrated Retrieval System
MODIS	Moderate resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
MSPPS	Microwave Surface and Precipitation Products System
MTSAT	Multi-Functional Transport Satellite
MW	Microwave
MYI	Multiyear ice
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite, Data, and Information Service
NIC	National Ice Center
NIR	Near-infrared

NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar Orbiting Partnership
NPROVS	NOAA Products Validation System
NWP	Numerical Weather Prediction
NWS	National Weather Service (US)
OCO	Orbiting Carbon Observatory
OHC	Oceanic Heat Content
OLR	Outgoing longwave radiation
OMPS	Ozone Mapping and Profiler Suite
POES	Polar-Orbiting Environmental Satellites
QuikSCAT	Quick Scatterometer
R2O	Research to Operations
RMS	Root-Mean-Square
SAR	Synthetic Aperture Radar
SBUV	Solar-Backscatter UltraViolet Spectrometer
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SHIPS	Statistical Hurricane Intensity Prediction Scheme
SMOPS	Soil Moisture Product System
SMOS	Soil Moisture-Ocean Salinity
SPC	Storm Prediction Center
SSFR	Solar Spectral Flux Radiometer
SSM/I	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
STAR	Center for Satellite Applications and Research
SV	Sailing Vessel
SWIR	Shortwave infrared
TCI	Temperature Condition Index
TIROS	Television Infrared Observation Satellite
TOPEX	Ocean Topography Experiment
TPW	Total Precipitable Water
TRMM	Tropical Rainfall Measuring Mission
TSM	Total Suspended Matter
UNESCO	United Nations Educational, Scientific and Cultural Organization
USCG	U.S. Coast Guard
USDA	U.S. Department of Agriculture
USDM	U.S. Drought Monitor
USGS	U.S. Geological Survey
VCI	Vegetation Condition Index
VHI	Vegetation Health Index
VIIRS	Visible Infrared Imager Radiometer Suite
WMO	World Meteorological Organization



In June 2012, Tropical Storm Debby churned off the coast of the Florida Panhandle, dumping in excess of 20” of rain over a 3 day period. On June 25th, the Suomi NPP satellite flew over the storm, collecting data from its suite of sensors including VIIRS, which captures data from the visible and infrared spectrum.

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