ATMOSPHERIC SCIENCE

Observing Weather from Space

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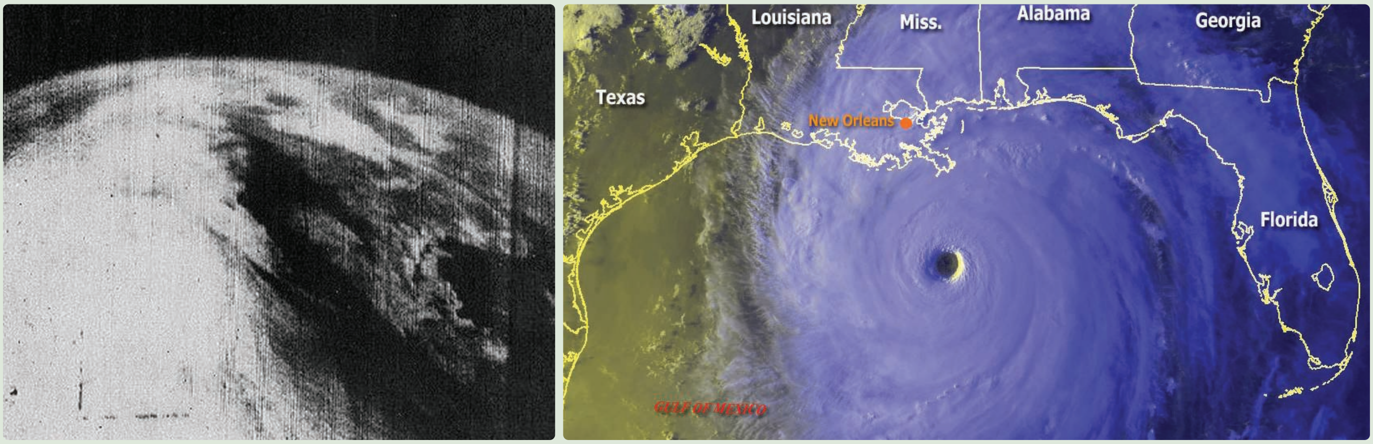
Since the first weather satellite was launched 50 years ago, satellite observations have revolutionized weather forecasting.

On 1 April 1960, the world's first weather satellite, the Television Infrared Observation Satellite 1 (TIROS 1), was launched from Cape Canaveral, Florida, into a 99-min orbit at an altitude of about 725 km. The cylindrical (1.1-m diameter, 0.48-m tall), 120-kg spacecraft was spin-stabilized, rotating between 8 and 12 times per min. It carried two television cameras that pointed parallel to the spin axis and could take 32 pictures per orbit (*1*). Although the results were modest by today's standards (see the figure), TIROS 1 revolutionized the field of meteorology.

TIROS 1 satellite, 1 April 1960 | **NOAA 15 satellite, 28 August 2005**



What a difference 50 years make. (Left) The first image from TIROS 1. Nova Scotia is in the lower right quarter. The television camera was pointing to the west. A cloud formation is visible in the lower left quarter. (**Right**) Hurricane Katrina on 28 August 2005 at 2332 UTC, as seen from the NOAA 15 satellite. The image is composed of visible (yellow) and infrared (blue) observations.

Weather forecasting is an initial-value problem: One observes the weather (preferably globally) at a particular time, and then uses equations or simple extrapolation to propagate the weather into the future. The complexities of integrating the equations and of modeling the physics of the three phases of water that exist on Earth (and which most people consider to be the weather) are not to be underestimated, but nor is observing the initial state of the weather. Due to the sheer size of Earth's atmosphere, 40,000 km in circumference, satellite platforms are the only ones from which the entire atmosphere can be observed. From land, only about one quarter of the atmosphere can be observed.

After 1945, the first cloud photographs were taken from cameras mounted on balloons and rockets. However, balloon- and rocket-mounted cameras could take pictures only very infrequently when a rocket or balloon was launched, not daily, as meteorologists needed. Meteorologists thus eagerly awaited the launch of a satellite carrying a cloud camera (*2*). Progress was rapid after the success of TIROS 1, which returned 19,389 meteorologically useful images in its 79-day life (*1*). In the next decade, the United States launched 24 civilian meteorological satellites, including the first Sun-synchronous satellite (Nimbus 1) and the first geosynchronous meteorological satellite (ATS 1); the former Soviet Union launched a similar number of meteorological satellites (*3*). All meteorologically important portions of the electromagnetic spectrum, from the microwave to the ultraviolet, were sampled for the first time. Succeeding decades have each seen dozens of meteorological satellites launched by countries around the world.

The first meteorological satellites were designed to take snapshots of clouds, which are the main feature in visible or infrared images (see the figure). From these images—especially from geosynchronous satellites, which allow "movies" of the weather to be made—meteorologists learned to identify and forecast meteorological systems such as low- and high-pressure systems, fronts, jet streams, severe thunderstorms, tropical storms, and snow storms (*4*, *5*).

Forecasters make short-term forecasts (up to 6 hours) largely by extrapolating the motion of weather systems observed with satellites. Almost all forecasts longer than 6 hours are made using numerical weather prediction (NWP) models. Satellite observations enable retrieval of the atmospheric properties necessary to initialize NWP models: temperature, humidity, wind direction, and wind speed as functions of pressure. Temperature and humidity are retrieved from measurements on the wings of gaseous absorption bands, either in the infrared or microwave parts of the spectrum. Winds can be measured by tracking clouds in geostationary infrared images, by measuring the backscattered radiation from the wind-roughened sea surface using satellite-borne radars, or by measuring the polarization of microwave radiation emitted and reflected by the ocean surface (*6*). Today, more than 95% of data available to NWP models come from satellites (*7*). By one measure of forecast accuracy, 5-day forecasts are now as good as 3-day forecasts were 25 years ago, and forecasts in the conventionally data-sparse Southern Hemisphere have become as accurate as those in the Northern Hemisphere (*8*).

In addition, meteorologically important quantities are now retrieved that are not yet well assimilated into NWP models. These include precipitation (from passive micro-

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wave sensors and radars); cloud cover and cloud phase (from traditional passive visible and infrared measurements and from newer active instruments); snow cover, sea ice cover, and soil moisture (mostly from passive microwave instruments, which can sense through clouds); smoke, dust, volcanic ash, and other aerosols (from a variety of passive sensors); and gases, including carbon dioxide, sulfur dioxide, and ozone (from infrared and ultraviolet spectrometers). All of these quantities will gradually become part of improved NWP models and forecasts.

In the 50 years since TIROS 1, many fields other than meteorology have benefited from space-based observations, including atmospheric science, climate studies, oceanography, hydrology, ecology, and geology (*9*). It is becoming increasingly clear that these fields are interrelated. When a volcano erupts, the dust becomes a meteorological problem and a threat to aviation. Changes in sea surface temperatures alter the tracks of storm systems. Changes in atmospheric composition affect climate and air quality. Future satellite sensors will thus serve a variety of fields. A list of missions has been recommended as a result of the U.S. National Research Council's decadal survey for Earth science (*10*, *11*), and many other missions are planned by other countries (*12*, *13*).

The first 50 years of space-based Earth observation progressed from crude observations to scientific understanding to stewardship of the atmosphere and of Earth. Today's space-based observations will likely appear crude in 50 years (*14*). The new observations will result in many scientific insights and should help humanity to weather what could be the worst of global warming and other environmental problems.

References and Notes

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ENGINEERING

Intelligent Infrastructure for Energy Efficiency

A substantial fraction of wasted energy can be recovered by extending insights from the architecture of the Internet to the infrastructure of buildings.

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Buildings use 40% of the primary energy supplied in the United States, and more than 70% of all generated electricity (*1*), primarily for heating, cooling, and lighting. About 20% of the energy used by buildings can potentially be saved by correcting faults, including malfunctions and unnecessary operation (*2*). Initial deployments of advanced control systems currently in development suggest that they can save an additional 10 to 20% (*3*). The energy efficiency resource recoverable through such improved building controls and fault detection corresponds to the output from hundreds of power plants, equivalent to more than one-third of the coal-fired power production in the United States (*1*). Realizing these substantial savings will require introducing intelligence into the infrastructure of buildings, to distribute the optimization of their operation and detection of their faults.

Intelligent infrastructure extends "smart grid" initiatives that seek to save energy by allowing utilities to manage loads, such as turning off air conditioners during peak demand (*4*). However, a grid cannot be smart if it is connected to dumb devices. Currently, modifying a building is costly and labor-intensive; it can cost $1000 to add a control point containing a $1 sensor to a building, requiring a skilled installer to connect it to a central controller that then must be reconfigured. This situation is analogous to computing and communications before the Internet, when terminals and telephones were connected to mainframes and central office switches.

The Internet allowed applications to reside where information is created and consumed, from reading e-mail to viewing virtual worlds. In this way, its applications are independent of how the network connecting them is constructed (*5*). This observation is equally applicable to building infrastructure: Sensors and actuators can compute and communicate to solve problems locally rather than having functions fixed by a central controller (*6*).

Many of the candidate standards for smart building systems are recreating rather than extending the development of the Internet. There are, however, important differences between high-performance buildings and networks. Installation lifetimes for buildings are measured in decades, and the cost of installation and maintenance can dwarf the cost of devices. Events can happen over seasons (such as cooling versus heating) rather than seconds, requiring efficient handling of slow rather than fast events. Operation must often be unsupervised, air and water as well as information must be moved, and people are an integral part of the building system. Each of these practical considerations presents new research challenges; they cannot be addressed simply by making better use of available technologies.

A testbed for intelligent infrastructure for energy efficiency (I2E), shown in panel A of the figure, consists of 100 nodes (*7*) that cost about $1 each but contain interfaces for sensors and loads, implement Internet Protocol (IPv6) communications over the dc control wiring already in the building, and provide an

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