OBSERVING EARTH

Even as **NEW SATELLITES** launch to observe air chemistry and climate, scientists worry about measurement longevity

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STUDYING COMPLEX environmental systems, such as atmospheric chemistry and climate, requires a global, long-term view—the view from a satellite.

"You can have access to regions that are very, very difficult to go study and make sustained measurements in, such as the polar regions, rainforests of Central America, and other areas that are under-instrumented and understudied," says Michael Gunson of the National Aeronautics & Space Administration.

Civilian Earth-observing satellites date to 1960, when NASA launched its first *Television Infrared Observation Satellite* to map cloud cover. The satellite worked for just 78 days, but it proved the potential of satellites to monitor environmental conditions from space.

Today, NASA counts 17 and the National Oceanic & Atmospheric Administration counts 15 active Earth-observing platforms in orbit. Some are testing out brand-new technology, such as the *Orbiting Carbon Observatory-2* (*OCO-2*), which launched in July and will measure atmospheric CO_2 with the resolution to characterize sources and sinks on regional scales. Others, such as the *Suomi National Polar-Orbiting Partnership* (*Suomi-NPP*) satellite, continue a decades-long series of measurements of temperature, water, and ozone.

They all make an essential contribution to environmental science. Aside from providing data from hard-to-reach places, they enable wide-angle views. For CO_2, for example, there are only about 100 monitoring stations around the globe. "That is just absolutely inadequate," says Inez Fung, a professor of atmospheric science at the University of California, Berkeley. "There's a lot of room for imagination for what goes on between the stations."

Over the next few years, NASA plans to launch several new satellites that will help researchers study chemistry both low and high in the atmosphere, as well as Earth's water cycle through soil moisture and ice-sheet measurements. Other countries are doing the same. But as critical as such satellites are for studying complex environmental systems, researchers are concerned about the future: There is no good path either in the U.S. or internationally to set and execute long-term priorities for space-based observations.

The current flagship of NASA's Earth science satellite missions is *Terra*. *Terra* launched in 1999 and carries five instruments: ASTER, which collects visible and infrared light to map Earth's land surface temperature, reflectance, and elevation; CERES, which monitors Earth's radiation budget and cloud properties; MISR, which uses reflected sunlight to illuminate atmospheric aerosol and cloud types and properties, as well as vegetation distribution; MODIS, which tracks aerosols and clouds with a wider view, along with snow and ice cover and photosynthetic activity; and MOPITT, which maps carbon monoxide and methane using infrared bands.

Other satellites launched in the early 2000s were also big platforms. *Aqua,* which is generally focused on Earth's hydrologic cycle, has its own CERES and MODIS plus additional instruments to better characterize atmospheric water vapor, clouds, precipitation, sea surface temperature and winds, sea ice, snow, and soil moisture. *Aura,* which looks at atmospheric chemis-

UP AND AWAY The *OCO-2* satellite launched in July and is starting to send back spectra to quantify CO_2 in Earth's atmosphere.

BILL INGALLS/NASA

try and dynamics, carries instruments that collectively can track O_3, H_2O, OH, HO_2, CO, CH_4, CH_2O, $C_2H_2O_2$, CH_3CN, N_2O, HNO_3, SO_2, ClO, HCl, BrO, and OClO. One instrument, called HIRDLS, also measured chlorofluorocarbons, but it ceased operating in 2008. Although most chemical measurements reveal only the total amount of a particular chemical from the bottom to the top of the atmosphere, the particular spectral bands of ozone allow researchers to differentiate how much is next to the Earth in the troposphere, where ozone is a health-harming pollutant, versus higher up in the stratosphere, where it serves to shield Earth from ultraviolet radiation.

MORE RECENT SATELLITE missions have tended to be more highly focused on one aspect of Earth's environmental system. *OCO-2* is one example. *OCO-2* carries spectrometers that look at the sunlight reflected off of Earth and measure two CO_2 absorption bands and one O_2 absorption band, all in the near-IR. The output is the mole fraction of CO_2 in dry air, with better precision and resolution than existing satellites provide. CO_2 doesn't vary by more than a percent from the bottom to the top of the atmosphere, "so you need to measure it extremely well," says Paul O. Wennberg, a professor of atmospheric chemistry at California Institute of Technology and part of *OCO-2*'s science team. *OCO-2* is just starting to send in its first data now, and although "things look great," Wennberg says, he's cautious about pinning a limit of detection on the measurements just yet. He hopes to get close to 0.5 ppm, compared with an overall CO_2 concentration of about 400 ppm.

And *OCO-2*'s spatial resolution is 3 km². "It's really the sharpest eye in the sky for CO_2," UC Berkeley's Fung says. Overall, *OCO-2* will provide a much better view of where CO_2 comes from and where it goes than scientists and policymakers currently have. "It's very difficult to do any carbon management strategy when you don't have good information," Fung says.

Beyond *OCO-2,* atmospheric chemists are also looking forward to the *Tropospheric Emissions: Monitoring of Pollution* (*TEMPO*) satellite, which is being developed now for launch in 2018 or 2019. In part, *TEMPO* will provide continuity from 10-year-old *Aura* by monitoring key pollution and air quality compounds: O_3, NO_2, SO_2, CH_2O, and $C_2H_2O_2$, along with water vapor, aerosols, and cloud properties. Other molecules, such as halogen oxides that come out of seawater, may also be possible, says Kelly Chance, a senior physicist at the Smithsonian Astrophysical Observatory and *TEMPO*'s principal investigator.

Aura, OCO-2, and many other satellites follow a so-called sun-synchronous orbit, which means that they orbit Earth in line with the sun, getting a global data set each day. *TEMPO,* in contrast, will sit in a so-called geostationary orbit and collect data only over North America, repeating its measurements every hour. Whereas *Aura*'s pollution-monitoring instrument has a spatial resolution of 13 km², *TEMPO*'s will be about 9.8 km². *TEMPO*'s view will reach far enough north to monitor emissions from the Alberta oil sands.

Scientists are hopeful that *TEMPO* will push forward their understanding of atmospheric chemistry. "Most of the previous work using satellite data has been focused on just getting the emissions right," says Ronald C. Cohen, a UC Berkeley chemistry professor and director of the Berkeley Atmospheric Science Center. "The next frontier is to see how the chemistry is different in different locations and how plumes evolve."

"What we're seeing now in the air pollution world is a transition from local to regional to global," adds Ross J. Salawitch, a professor of atmospheric and oceanic science at the University of Maryland. "It used to be that pollution was so bad that we had to control local sources. In a lot of U.S. states that's been done, so now we need to pinpoint what's coming from further away. Satellite data are vital for this." Although *TEMPO*'s sole focus will be North America, similar satellites are being developed by Europe and South Korea to monitor their parts of the world. Computer models may help connect the data sets, even as better data will also help to improve the models.

For all the immediate importance of measuring pollutants for air quality and health, the bigger picture for Earth is climate. And for climate, satellites must measure water. "Water is the big feedback," says NASA's Gunson, who is program manager for global change and energy at the Jet Propulsion Laboratory (JPL) and also project scientist for *OCO-2*. "The hydrologic cycle is where we will see some of the most important consequences of climate change," whether the effects are in sea-level rise or precipitation and the availability of freshwater. The hydrologic cycle is also the source of a lot of uncertainty about the consequences of climate change.

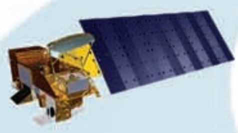
Terra, Aqua, and other satellites are perfectly positioned to help assess the amount of water vapor in the air; how efficiently water turns into precipitation through clouds; distribution of rain, snow, and ice; soil moisture; connections between ocean salinity, density, and weather patterns; and links between sea level and ocean heat distribution.

But to make those assessments and understand the broader interplay among atmospheric chemistry, hydrology, and climate—and what global warming might mean on a local scale—requires long-term measurements. Climate is such a complicated problem that one or two years of observations are insufficient. It's only after a decade or more that researchers can start to tease out trends that yield clues to the underlying physical processes. Those

Aqua

Orbit: 705 km; collects data globally
Launched: 2002
Design life: 6 years
Initial NASA cost: $1.3 billion
NASA 2015 budget request: $32.6 million
International partners: Brazil, Japan

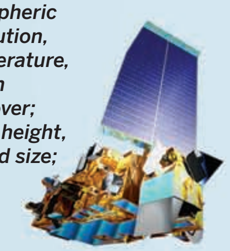
Collects data on precipitation, ocean evaporation, ocean temperature, sea ice, snow, soil moisture, clouds, aerosols, and Earth's radiation budget to improve understanding of Earth's water cycle and climate systems.



Terra

Orbit: 705 km; collects data globally
Launched: 1999
Design life: 6 years
Initial NASA cost: $1.9 billion
NASA 2015 budget request: $30.8 million
International partners: Canada, Japan

Contributes to atmospheric, carbon cycle, ecosystem, and climate studies through measurements of atmospheric temperature, water vapor distribution, CO_2, and CH_4; land surface temperature, vegetation and snow cover; ocean chlorophyll production and ice cover; cloud properties including types, height, and water droplet distribution and size; Earth's radiation budget.



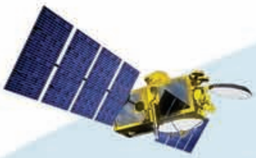
EYES ON EARTH

Some Earth-observing satellites aid weather prediction and others take high-resolution land images, but a subset focuses on understanding atmospheric chemistry and climate.

Jason-2/OSTM
Ocean Surface Topography Mission/Jason-2

Orbit: 1,336 km; collects data globally
Launched: 2008
Design life: 3 years
Initial NASA and NOAA cost: $195 million
2015 budget request: $2.1 million
International partners: Europe, France

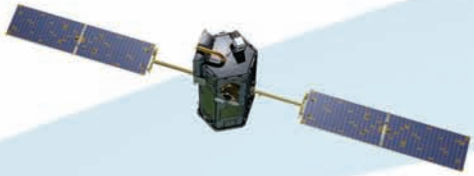
Measures sea surface height to assess climate variability and water and energy cycles. Changes in sea level provide information on heat distribution in the upper ocean. Jason-3 is scheduled to launch in 2015.



OCO-2
Orbiting Carbon Observatory-2

Orbit: 705 km; collects data globally
Launched: 2014
Design life: 2 years
Initial NASA cost: $468 million

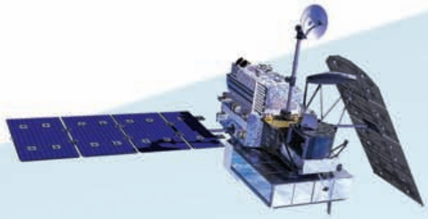
Measures atmospheric CO_2 with the resolution to characterize sources and sinks on regional scales.



GPM Core Observatory
Global Precipitation Measurement Core Observatory

Orbit: 407 km; collects data globally
Launched: 2014
Design life: 3 years
Initial NASA cost: $933 million
International partner: Japan

Profiles rain and snow distribution, amount, rate, and heat release to improve understanding of Earth's water and energy cycle and improve forecasting of extreme weather events.



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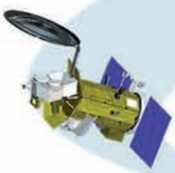
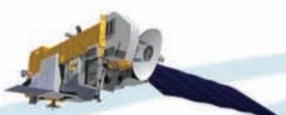
To view an interactive version of this article's graphic that includes videos of the various satellites, go to http://cenm.ag/satellites.



SAC-D/Aquarius

Orbit: 657 km; collects data globally
Launched: 2011
Design life: 3 years
Initial NASA cost: $304 million
NASA 2015 budget request: $5.1 million
International partner: Argentina

Maps sea surface salinity, along with temperature, precipitation, wind speed, sea ice, and water vapor, for better understanding of the global water cycle and ocean circulation.



Aura

Orbit: 705 km; collects data globally
Launched: 2004
Design life: 5 years
Initial NASA cost: $990 million
NASA 2015 budget request: $26.2 million
International partners: Netherlands, Finland, U.K.

Provides information on atmospheric chemistry and air quality, including exchange of energy and molecules between the troposphere and stratosphere and chemistry-climate interactions. Molecules monitored include O_3, H_2O, OH, HO_2, CO, CH_4, CH_2O, $C_2H_2O_2$, CH_3CN, N_2O, NO_2, HNO_3, SO_2, ClO, HCl, BrO, and OClO.

CALIPSO & CloudSat
CALIPSO is Cloud-Aerosol Lidar & Infrared Pathfinder Satellite Observations

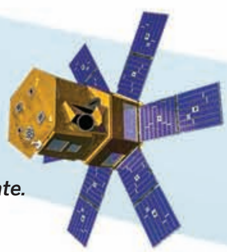
Orbit: 705 km; collects data globally
Launched: 2006
Design life: 3 years
Initial NASA, Department of Energy, and U.S. Air Force cost: $502 million
NASA 2015 budget request: $14.9 million
International partners: France, Canada

Provide high-resolution vertical profiles of aerosols and clouds, along with their climate effects, and estimates of how efficiently the atmosphere produces rain. The Cloud-Aerosol transport System (CATS) instrument, scheduled to launch later this year for installation on the International Space Station, is to provide continuity for CALIPSO measurements.

SORCE
Solar Radiation & Climate Experiment

Orbit: 645 km; collects data from sun
Launched: 2003
Design life: 5 years
Initial NASA cost: $129 million
NASA 2015 budget request: $3.4 million

Monitors solar irradiance to better understand solar variability and its effects on Earth's atmosphere and climate.



NOTE: All dollar amounts are in 2014 dollars.

NASA IMAGES

UPCOMING

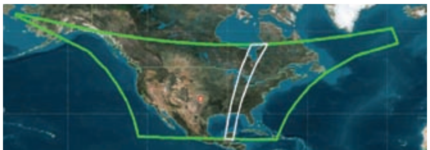
Satellite missions planned for the next few years will enhance and continue Earth observations

SMAP
Soil Moisture Active-Passive
Orbit: 685 km; collects data globally
Planned launch: Fall 2014
Design life: 3 years
Estimated NASA cost: $917 million
Will analyze soil moisture and whether it is frozen or thawing to understand the processes that link water, energy, and carbon cycles.

SAGE III ISS
Stratospheric Aerosol & Gas Experiment III on the International Space Station
Orbit: 400 km; collects data globally
Planned launch: 2016
Design life: 3 years
Estimated NASA cost: $126 million
International partner: Europe
Will measure vertical distribution of aerosols and O_3, as well as H_2O, NO_3, and OClO in the upper parts of the atmosphere to improve understanding of chemical processes.

ICESat-2
Ice, Cloud & Land Elevation Satellite-2
Orbit: 400 km; collects data globally
Planned launch: 2017
Design life: 3 years
Estimated NASA cost: $1,064 million
Will measure the polar ice sheets to quantify changes in ice-sheet mass and provide insight into the mechanisms that drive that change and how energy, mass, and moisture exchange among ice, ocean, and atmosphere.

TEMPO
Tropospheric Emissions: Monitoring of Pollution
Orbit: 35,786 km, collects data over North America
Planned launch: 2017
Design life: 2 years
Estimated NASA cost: $168 million
Will collect hourly, high-spatial-resolution measurements of tropospheric O_3, NO_2, SO_2, CH_2O, and aerosols to assess pollution effects on climate change and air quality. To be complemented by similar satellites over Europe and Asia.


KEEPING TRACK *TEMPO* will assess key air pollution compounds, repeating slices over North America hourly.

GOES-R
Geostationary Operational Environmental Satellite—R series of four satellites
Orbit: 35,800 km; collects data over Western Hemisphere
Planned launches: 2016, 2017, 2019, 2025
Design life: 10 years per satellite
NOAA 2015 budget request: $981 million
Will continue satellite series that first launched in 1975. Will provide information for weather forecasts, as well as track vegetative health, fire, volcanic ash, aerosols, O_3 and SO_2, and solar events.

JPSS
Joint Polar Satellite System, two satellites
Orbit: 800 km; collects data globally
Planned launches: 2017, 2022
Design life: 7 years per satellite
NOAA 2015 budget request: $916 million
Will continue satellite series that first launched in 1960 and that includes the current Suomi National Polar-Orbiting Partnership satellite, which launched in 2011. Will provide information for weather forecasts, as well as monitor O_3 distribution and temperature and moisture profiles to support long-term climate monitoring.

NOTE: All dollar amounts are in 2014 dollars.
SOURCES: NASA, NOAA

processes can then be used to improve climate models to understand things such how climate change will affect air quality or resources, says Anne R. Douglass, who is the *Aura* project scientist and helps develop the NASA Goddard Earth Observing System Chemistry Climate Model.

But *Terra* is 15 years old, *Aqua* is 12, and more satellites launching now have design lives of just three years. They'll probably last longer, but that's small comfort when it can take a decade to plan, build, and launch a new one. Scientists fret that the U.S. has struggled to set up a mechanism through which long-term measurement priorities are set and executed.

"NASA is an agency that prides itself in doing the first and the best thing, while NOAA has traditionally been more of a long-term operational agency," Caltech's Wennberg says. A "valley of death" between the agencies on the transition from research instruments to sustained monitoring got even worse when an ill-fated attempt to merge the U.S. civil and military meteorological satellite programs was canceled in 2010 because of cost overruns, and NOAA retrenched to focus more closely on weather at the expense of other monitoring.

Recession-era budget cuts didn't help matters, either. NOAA's existing satellite program already consumes about 40% of its budget, notes Antonio J. Busalacchi Jr., director of the Earth System Science Interdisciplinary Center at the University of Maryland. Increasing the budget for satellites might mean decreasing the funds available for, say, the fisheries service or nonsatellite oceanic and atmospheric research. Even NOAA's weather satellites, unequivocally considered essential for weather forecasting, may see a gap in upcoming years if existing instruments fail before new ones launch.

THE SITUATION HAS left NASA building "wonderful new sensors to measure things we really want to understand," Wennberg says, with little hope that they will find their way onto long-term missions.

Researchers do see some indications that things might be turning around. The White House Office of Science & Technology Policy produced the first National Strategy for Civil Earth Observations in 2013, and the National Science & Technology Council released a National Plan for Civil Earth Observations in July. The documents are more frameworks for how to assess projects rather than a true path forward, but scientists see it as progress.

A more general satellite trend toward miniaturization and packaging instruments into 10-cm "CubeSats" rather than the bus-like *Aura* also bodes well for sustainable programs. "My view is that the day is not far away before we can do really meaningful science" on relatively tiny platforms, says Graeme Stephens, director for the Center for Climate Sciences at NASA JPL. The smaller sizes require fewer resources to build and also cost far less to launch. Commercial spaceflights may also provide lower-cost launch options.

Ultimately, a long-term outlook is important not only to understand the complex systems of atmospheric chemistry and climate, but also for how to inform decisions about resource management or food security. Twenty years ago, climate change was "a research problem that had a certain degree of abstract nature to it because we weren't living in such rapidly changing times," Gunson says. "Now we have these crises, like droughts that start to affect water availability. The question is, How do we provide information to address those problems and identify adaptation strategies?" ■