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Clouds, aerosols, and all that jazz

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Touring the atmosphere aboard the A-Train

feature article

Tristan S. L'Ecuyer and Jonathan H. Jiang

A convoy of satellites orbiting Earth measures cloud properties, greenhouse gas concentrations, and more to provide a multifaceted perspective on the processes that affect climate.

Tristan L'Ecuyer (tristan@atmos.colostate.edu) is a research scientist in the department of atmospheric science at Colorado State University in Fort Collins. **Jonathan Jiang** (jonathan@mls.jpl.nasa.gov) is a research scientist at NASA's Jet Propulsion Laboratory in Pasadena, California.

Growing evidence indicates that human activity is altering the climate in significant and potentially hazardous ways. The most recent assessment from the Intergovernmental Panel on Climate Change asserts that global temperature may rise by 2–5 °C (4–9 °F) during the next 100 years in response to rising greenhouse gas concentrations.[1] Current predictions also suggest that regional climates may experience significant changes in the frequency and intensity of precipitation, shifts in surface vegetation and soil fertility, and rises in global sea level, to give some examples. Indeed, some changes are already evident, including the dramatic reduction in size of many glaciers, the rapid shrinking of the summertime Arctic ice cap, and a 20-cm rise in sea level since preindustrial times. Predictions of future climate, however, are predicated on model simulations. Of necessity, such models approximate climate scientists' often incomplete knowledge of the fundamental physical processes that govern the evolution of the climate system. Consequently, significant uncertainties remain in current-climate change projections, particularly at the regional level.[2]

Central to climate modeling is the challenge of accurately representing both the water cycle, which governs the distribution of water around the planet, and the exchange of heat between atmosphere, surface, and space. The global energy and water cycles, in turn, are intimately coupled to the large-scale atmospheric and oceanic circulation patterns that redistribute the surplus of radiative energy received in the tropics to higher-latitude regions that radiate away more energy than they receive from the Sun. Those large-scale atmospheric circulations are also strongly coupled to clouds and rainfall that can influence regional circulations by redistributing energy in the atmosphere. Indeed, the largest source of uncertainty in current projections of future climate is from incomplete knowledge of the feedbacks through which clouds can either amplify or diminish temperature changes induced by greenhouse gases.[3]

To better understand the climate system, climate scientists need to quantify the complex relationships that connect water in all three phases to heat exchanges between the surface, atmosphere, and space; to aerosols; and to trace gases. That is a daunting task, given the sheer number and diversity of measurements and parameters involved, but a one-of-a-kind constellation of satellites collectively known as the A-Train is helping scientists to meet the challenge.

A little history

The idea behind the A-Train emerged in the mid-1990s, as engineers and scientists were developing the *Aura* mission, then called *EOS Chem*. The *Aura* satellite had to be Sun synchronous, meaning that it must always cross the equator at the same local time, and in order for it to measure solar backscatter, the crossing time had to be within 1.5 hours of local noon. Otherwise, the orbit was unconstrained. Since the infrastructure of the *Aura* spacecraft was identical to that of its older sister *Aqua*, which was dedicated to water- and energy-cycle measurements, the scientists and engineers decided that *Aura* would follow its older sibling at an altitude of 705 km and an inclination of 98.2°. That way, the *Aqua* launch computations could simply be updated and applied to *Aura*. Due to limitations in data transmission rates, however, mission engineers decided that *Aura* should fly 15 minutes (6300 km) behind *Aqua*.

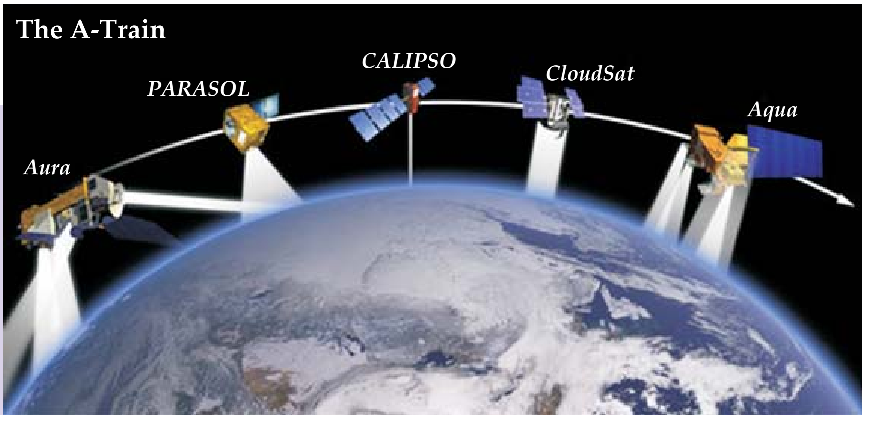

Figure 1. The A-Train constellation included five satellites and more than a dozen instruments during the period 2006–09. *PARASOL* has since dropped out, but at least one new satellite will join the train within the next couple of years. Some of the A-Train's instruments observe wide swaths of Earth's surface and atmosphere; others observe narrower regions in greater detail.

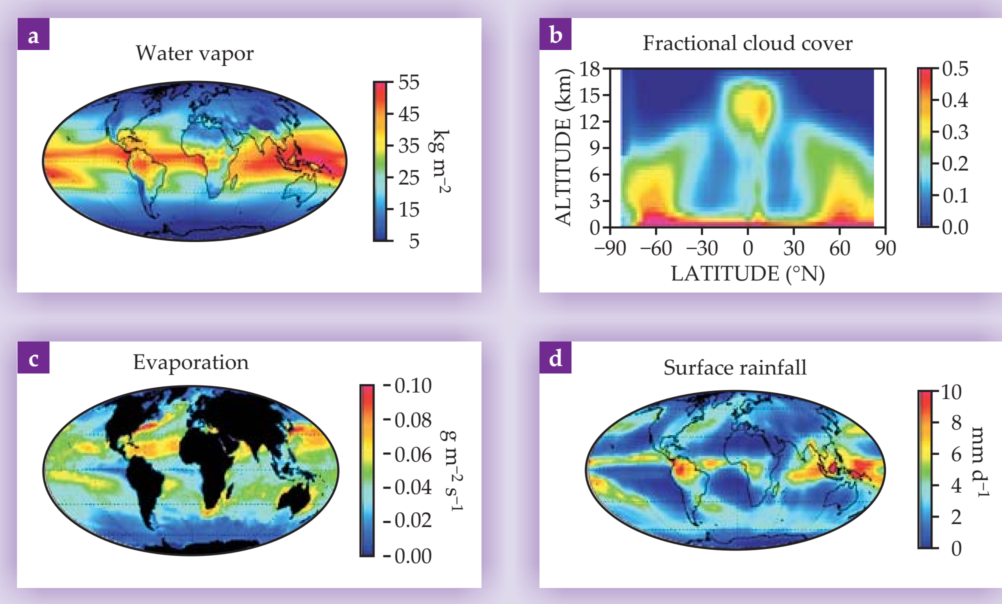

Figure 2. The global water cycle is the set of processes in which water evaporates from Earth's surface, moistens the atmosphere, is redistributed horizontally and vertically by atmospheric circulations, condenses into clouds, and falls back to Earth as precipitation. As these measurements from the A-Train convoy of satellites show, water vapor concentrations tend to be largest in the tropics **(a)**, where clouds form at the highest altitudes **(b)**. The horizontal and vertical distributions seen in panels a and b can be explained by the enhanced evaporation from warmer waters in the tropics **(c)** and atmospheric circulations that transport water vapor toward the equator. The convergence of water vapor in the tropics leads to a band of enhanced precipitation near the equator, called the Intertropical Convergence Zone, and to a large area of intense precipitation in the western Pacific Ocean extending southeast, known as the South Pacific Convergence Zone **(d)**. Also evident in panel d are the mid-latitude storm tracks, paths that storms often follow off the coasts of North America and Asia, and the widespread precipitation band between 45° S and 60° S. Sailors refer to those latitudes as the roaring 40s and furious 50s because of the persistent westerly winds and stormy weather there. In panel a, the water vapor is given as a column density. In all panels, data are averages over the year 2007. (Panel c courtesy of Carol Anne Clayson and the GEWEX SeaFlux project.)

Meanwhile, NASA was developing a new mission that would, for the first time, combine spaceborne radar and lidar (light detection and ranging) to simultaneously measure the vertical structure of clouds and aerosol layers in the atmosphere. Due to budget constraints, the mission was split into two separate proposals—*CALIPSO* (*Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation*), which was focused on profiling aerosols and thin clouds with lidar, and *CloudSat*, directed toward profiling thicker clouds using radar. The two missions competed against one another and several others to be part of NASA's Earth System Science Pathfinder Program, and both were selected for further development. Unaware that *Aura* was already planned to follow *Aqua*, the *CALIPSO* and *CloudSat* teams also requested orbits close behind the *Aqua* spacecraft to take advantage of its cloud and humidity measurements. Across the Atlantic, France's CNES had plans to launch a small satellite called *PARASOL* (*Polarization and Anisotropy of Reflectances for Atmospheric Sciences Coupled with Observations from a Lidar*), whose imaging polarimeter could also benefit greatly from coordination with *Aqua*'s higher spatial resolution measurements.

As scientists and engineers refined their mission plans, they began to fully appreciate the potential advantages of formation flying. A single platform could not accommodate the mass and power demands of all the missions' instruments. Moreover, if they were all crowded together on a single craft, the sensors would get in each others' way and interfere electronically. Carefully coordinating the orbits of five individual satellites, however, would enable researchers to benefit from a unique multisensor perspective of our planet. Figure 1 shows the resulting convoy of satellites as it was configured in 2006–09. During that period, it comprised *CloudSat*, *CALIPSO*, and *PARASOL*, bracketed by *Aqua* and *Aura*, two of the cornerstones of NASA's Earth Observing System program. The unique satellite configuration led *Aura* project scientist Mark Schoeberl to coin the name A-Train, after the famous 1930s jazz piece composed by Billy Strayhorn for the Duke Ellington Orchestra.

Within a few years after the launch of *Aura* in 2004, data transmission rates had improved sufficiently. Thus, over the course of a year ending in May 2008, *Aura* was gradually moved to within 7 minutes of *Aqua*. The closer proximity enabled better coordination between the two satellites. In particular, since clouds change very little in 7 minutes, the move meant that *Aqua* cloud observations could be used to improve *Aura* trace-gas measurements. Launched in 2006, *CloudSat* and *CALIPSO* were placed in a tight formation, with a separation of 12.5 s or 93.8 km. The satellites are so close that *CloudSat* must make regular orbit maneuvers to compensate for the different atmospheric drag it experiences. Since the launch of the two satellites, *CALIPSO*'s lidar beam and *CloudSat*'s radar beam have coincided at Earth's surface more than 90% of the time; that remarkable pointing precision has allowed data from the two spacecraft to be used in tandem for many applications. Launched in 2004, *PARASOL* flew an average of 30 s behind *CALIPSO* until decoupled from the A-Train on 2 December 2009 because it no longer had enough fuel to match the orbital maneuvers of the other satellites.

The A-Train perspective

The satellites in the A-Train carry both active instruments that transmit and receive signals and passive sensors that only receive them. Together the satellites view Earth from the UV to the microwave—a wavelength span of four orders of magnitude.[4] That wavelength diversity, coupled with the distinct viewing geometries and scanning patterns of the instruments aboard the A-Train, provides composite information about a wide variety of climate parameters. At the front of the train, *Aqua* carries several instruments that obtain, for example, pro-

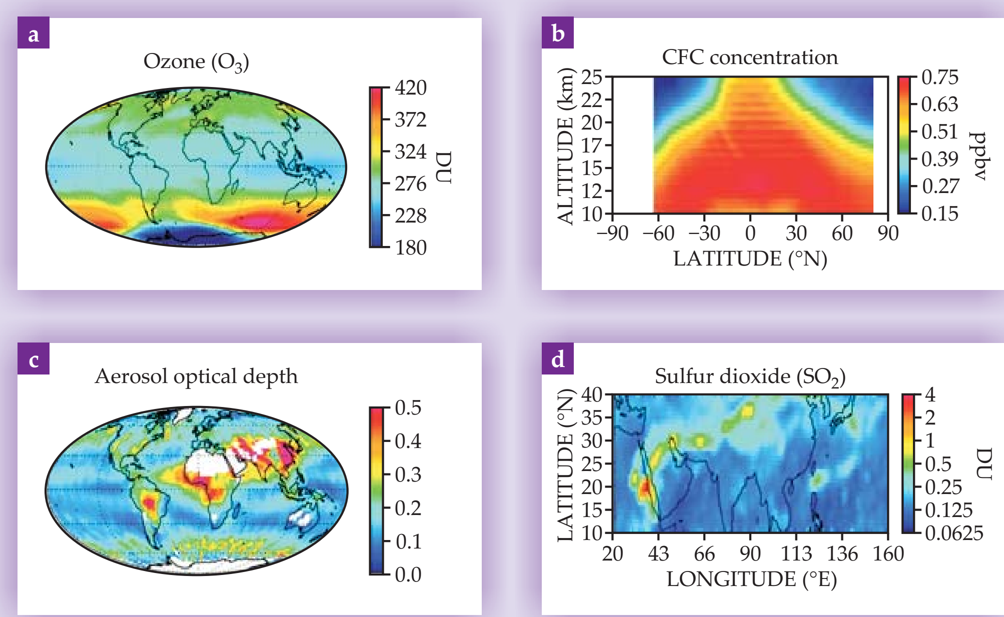

Figure 3. Trace gases and aerosols affect public health and reveal surface activity on Earth. **(a)** Measurements of the ozone distribution taken in September 2007 from the A-Train satellites clearly reveal the ozone hole over the Antarctic. Thickness is measured in Dobson units (DU): 100 DU corresponds to a quantity of ozone that would give a 1-mm-thick layer at a temperature of 0 °C and a pressure of 1 atmosphere. **(b)** The A-Train also measured the concentrations of two long-lived chlorofluorocarbons (CFCs) that catalyze ozone depletion. The depletion reactions occur on the surfaces of ice particles that make up the polar stratospheric clouds that often exist over Antarctica. The concentrations are given in parts per billion by volume (ppbv). **(c)** The distribution of aerosol particles in the atmosphere shows evidence of dust and biomass burning in Africa and the Amazon region. Also visible are aerosols from industrial activity in eastern China. The optical depth shown here is a logarithmic measure of the amount of radiation that is absorbed or reflected by atmospheric aerosols. **(d)** The sulfur dioxide emissions seen here originated with the 30 September 2007 eruption of the Jebel al-Tair volcano in the Red Sea. As the map shows, they were carried over a large portion of Asia and the western Pacific Ocean. Volcanic emissions can affect air travel, reduce air quality, and act as a precursor for sulfate aerosols that can exert a significant influence on climate.

files of temperature, water vapor, and surface rainfall—important components of the atmospheric branch of the global water cycle. *Aqua* also measures cloud properties, aerosol concentrations, and radiative fluxes at the top of the atmosphere—all key quantities related to the global radiation budget.

CloudSat's and *CALIPSO*'s active radar and lidar sensors add a vertical dimension to *Aqua* observations by probing the internal structure of cloud and aerosol layers along a narrow strip near the center of the much wider *Aqua* swath. The complementary multi-angle measurements of *PARASOL* in the visible and IR enable climate scientists to infer the size, shape, orientation, and even chemical composition of atmospheric aerosols. Together, the data from the four satellites yield new information about the three-dimensional structure of clouds and aerosols in Earth's atmosphere. Armed with those data, scientists can quantitatively determine how clouds and aerosols influence global energy balance.

The caboose of the A-Train is the *Aura* satellite. Launched in 2004, its primary focus is atmospheric composition.[5] *Aura*'s instruments provide high-resolution maps that show the vertical distributions of greenhouse gases and gases central to ozone depletion. Its observations provide an additional source of aerosol and thin-ice-cloud information that complements similar measurements obtained from the other instruments aboard the train.

A thorough discussion of the A-Train's measurements and how they are applied is beyond the scope of this article, but a complete list of the convoy's sensors and their primary purposes is included in an online supplement. Here we offer examples of observations grouped around two central themes: the global water cycle and atmospheric composition. Figure 2 depicts A-Train measurements of surface evaporation, surface rainfall, and water-vapor and cloud distributions. The data allow scientists to monitor each of those major components of the water cycle and quantify water exchanges between the ocean, atmosphere, and land.

Atmospheric aerosols and trace gases can play an important role in global energy balance. But they also affect public health both regionally in the form of pollution and on larger scales through chemical processes such as the catalyzation of ozone depletion. For those reasons, scientists and policymakers are eager to obtain accurate assessments of atmospheric composition. The instruments aboard the A-Train provide complementary, near-global measurements of aerosols and many atmospheric trace gas species from which climate scientists glean new information about the chemical and physical processes in Earth's atmosphere. Figures 3a and 3b, for example, show a clearly visible ozone hole over Antarctica and distributions of chlorofluorocarbons implicated in ozone destruction. Such observations should become an invaluable resource for monitoring the anticipated ozone recovery in the coming years. Figures 3c and 3d show how aerosol or trace gas distributions offer a unique perspective on such natural events as forest fires or volcanic eruptions.

Rapid change in the Arctic

In addition to supporting a diverse population of marine mammals and several human cultures, Arctic sea ice significantly affects the climate system. It reflects solar energy during the summer; it modifies the exchange of heat, gases, and momentum between the atmosphere and the Arctic Ocean; and it affects ocean circulations by modifying the distribution of fresh water. (See the article by Josefino Comiso and Claire Parkinson in Physics Today, August 2004, page 38.) As a result, observed changes in the concentration, extent, thickness, and growth and melt rates of Arctic sea ice have important social and climate implications. Climate scientists estimate, for example, that the area covered by Arctic sea ice in September, the month when coverage is at a minimum, has decreased by an average of approximately 60 000 km^2 per year since satellite observations of the region began in 1979.

Recent sea ice extents have been especially low. In September 2007, for example, sea ice covered just 4.3 million km^2, the smallest value in recorded history.[6] The observed rate of sea-ice retreat in 2007 far exceeded that predicted by climate models, and the discrepancy initially fueled a great deal of concern in the climate community. The startling 2007 ice loss was captured in detail by A-Train sensors. Those observations, especially welcome because in situ measurements covering the Arctic Ocean are difficult to make, provided new insights into the processes that connected atmosphere, ocean, and sea ice and contributed to the Arctic ice melt. Basing their analysis in part on A-Train observations, climate scientists are now in wide agreement that a perfect storm of anomalous weather conditions was responsible for the rapid decline observed in 2007.

Figure 4 shows A-Train observations associated with the 2007 sea ice minimum. In both 2006 and 2007, sea ice coverage was significantly less than the 1979–2000 average, but the observations from 2007 dramatically reveal the sudden melting of a large fraction of the ice that normally blankets the Beaufort Sea. Anomalously high winds in the summer of 2007 contributed to the extreme ice loss by causing a relatively rapid compression of sea ice and its quicker-than-normal transport into warmer waters outside the Arctic.[6] The lower panels of figure 4, however, give evidence that the summertime melting may have been enhanced by another mechanism:[7] Measurements from *CloudSat* and *CALIPSO* indicate that summertime cloud cover in the region decreased by 16% from 2006 to 2007. Irradiance calculations based on those observations suggest that, on average, clearer skies in the summer of 2007 allowed an additional 32 W/m^2 of sunlight to reach the surface.

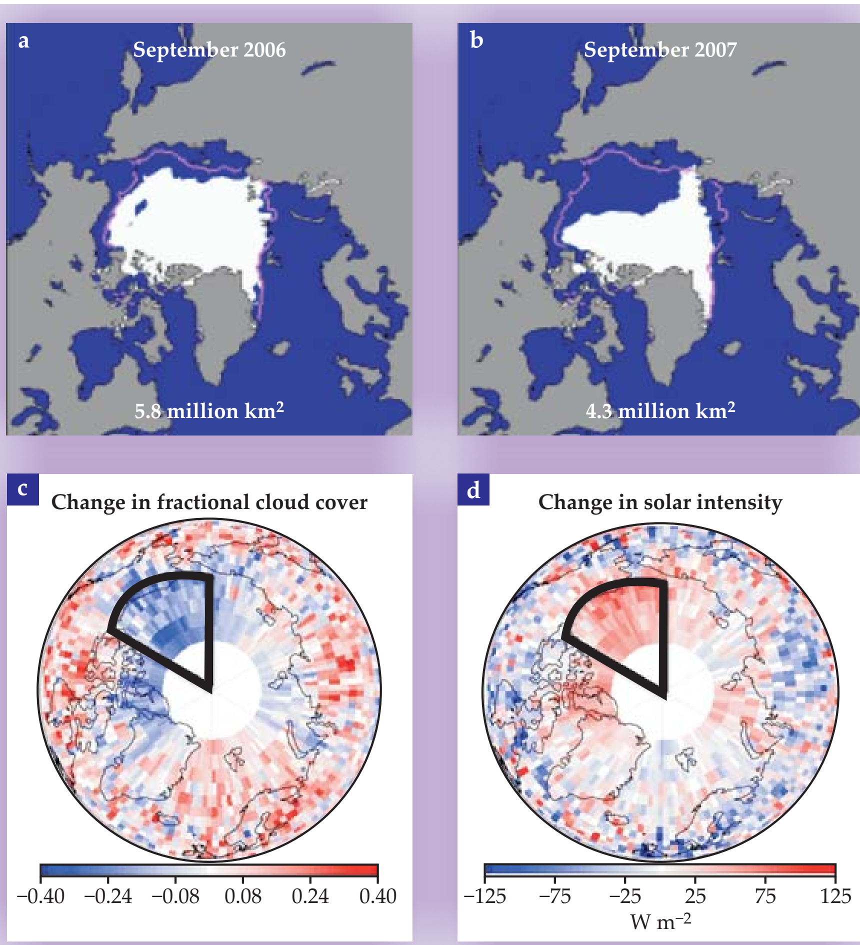

Figure 4. Clouds likely were a factor in the dramatic retreat of Arctic sea ice in the summer of 2007. **(a)** In 2006 the extent of Arctic sea ice as measured by the *Aqua* satellite was significantly less than the 1979–2000 long-term average shown in pink. **(b)** In 2007 *Aqua* measurements revealed sea ice coverage to be at an all-time low. (Panels a and b courtesy of the National Snow and Ice Data Center.) **(c)** Average cloud coverage over the Beaufort Sea region (within the black slice) decreased dramatically between summer (June–August) 2006 and the same period in 2007, according to *CloudSat* and *CALIPSO* observations. **(d)** Associated with the decreased cloud coverage was an increase in solar intensity reaching the surface. (Panels c and d adapted from ref. 7.)

Back-of-the-envelope calculations suggest that the additional energy delivered in the summer of 2007 could increase surface ice melt by 0.3 m. It could also warm the surrounding ocean's near-surface mixed layer by 2.4 K and thus significantly enhance basal ice melt. Moreover, atmospheric temperature and moisture observations from *Aqua* sensors indicate that the decrease in cloudiness in 2007 was related to increased air temperatures and decreased relative humidity associated with persistent high pressure in the region. In sum, many factors seem to have combined to cause the rapid decline in Arctic sea ice in 2007. A-Train measurements provide evidence that increased solar energy at the surface, associated with reduced cloudiness, was one of the important components contributing to the event.

Aerosols: Not to be sneezed at

In addition to their effects on air quality, aerosol particles surely affect Earth's radiation budget, but it's not clear just what that effect is. Depending on their composition, some aerosols scatter solar radiation and tend to cool the planet, whereas others absorb radiation and potentially warm Earth. Moreover, the impact of aerosols strongly depends on the presence or absence of clouds. For instance, a thick dust layer over a dark ocean surface can significantly increase the amount of sunlight reflected back to space, but the same layer above an already bright cloud probably won't have much effect. The combination of active and passive sensors on the A-Train have dramatically improved scientists' understanding of the spatial covariation of clouds and aerosols. We have recently discovered, for example, that absorbing aerosols produced from biomass burning exert a net cooling on the environment when the underlying cloud coverage is less than 40% but lead to warming in more overcast conditions.[8]

Aerosols can also substantially modify the characteristics of clouds. Atmospheric physicists have long recognized, for example, that large concentrations of sulfate aerosols might lead to smaller-sized droplets in a cloud; as a result, a cloud with a given amount of water would be brighter in a more polluted environment.[9] That so-called first aerosol indirect effect may be enhanced by the increased concentration of smaller cloud droplets inhibiting precipitation and thus increasing cloud lifetime and cloud cover.[10] Given that low clouds account for about half of the solar energy Earth reflects back to space, the combination of brighter and longer-lived clouds could cause a significant cooling that partially offsets the warming from increased greenhouse gas concentrations. Exactly how much cooling is realized has been a topic of considerable debate in the climate community; the sensitivity of clouds to aerosol concentration is a strong function of atmospheric dynamics, local temperature and humidity, and even cloud properties themselves.[11]

To help resolve the debate, the A-Train's diverse instruments are measuring the bulk response of cloud systems to changes in aerosol concentrations; figure 5 shows some of what we have learned. Clouds made from drops of liquid grow deeper, contain smaller droplets, rain less frequently, and appear brighter from above in the presence of large concentrations of small aerosol particles.[12] Moreover, A-Train sensors have furnished groundbreaking measurements of how aerosols affect ice clouds. *Aura* observations of carbon monoxide, a pollutant that often accompanies aerosols from biomass burning, have been combined with *Aqua* measurements of clouds located at the same positions as the CO. Together, they demonstrate that polluted ice clouds generally contain smaller particles than cleaner clouds and are accompanied by weaker precipitation.[13] A knowledge of aerosol–cloud interactions is important for climate prediction, and it is admittedly difficult to prove cause and effect by correlating satellite measurements. The A-Train, though, with its ability to simultaneously measure a wide range of cloud properties in both polluted and clean environments, provides several distinct measures of how clouds respond to aerosols. That the different perspectives are all generally consistent lends credence to A-Train-based analyses of aerosol effects on global scales.

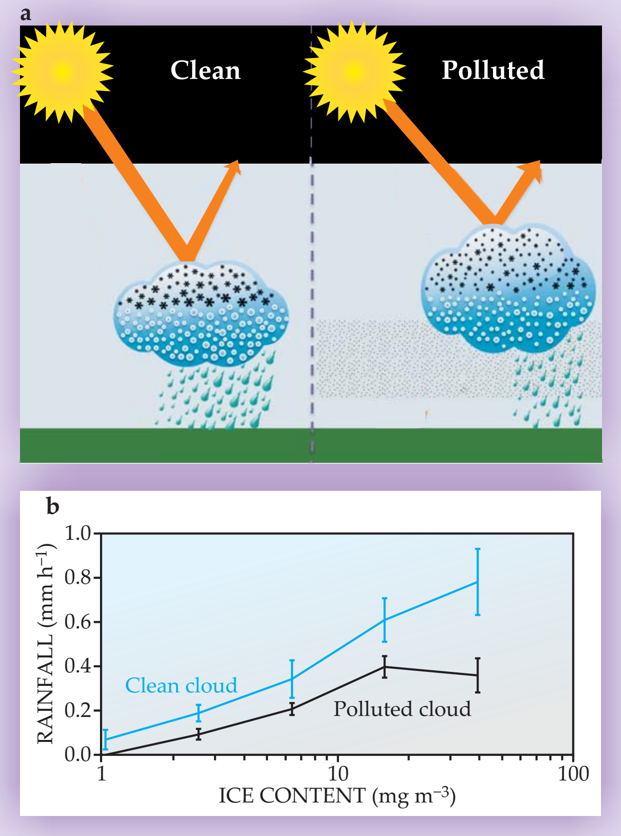

Figure 5. Pollution changes cloud properties. (a) Clouds in polluted environments tend to have smaller water drops and ice crystals than those in cleaner environments. As a result, dirty clouds are less likely to generate rainfall and are generally brighter than clean clouds. **(b)** Data from the *Aura* and *Aqua* satellites, in conjunction with rainfall observations from the *Tropical Rainfall Measuring Mission*, demonstrate that for a given ice content, clouds in polluted environments produce less intense rainfall. (Adapted from ref. 13.)

Toward improved climate forecasting

Robust predictions of future climate are essential if the world's policymakers are to develop sound strategies for mitigating and adapting to future climate change. Yet despite the marked progress in climate models over the past 20 years, uncertainties in cloud feedbacks, regional precipitation, and other aspects of climate have improved little since the Intergovernmental Panel on Climate Change's first assessment in 1990. The A-Train carries tools for evaluating how well climate models represent several aspects of present-day energy and water cycles, atmospheric composition and transports, and surface–atmosphere exchanges. Such tests are critical because accurate prediction of climate variability on decadal and longer time scales requires that models be capable of simulating current climate and short-term variations such as the diurnal and annual solar cycles and the year-to-year variations associated with the El Niño Southern Oscillation.

Climate scientists have shown, for example, that models generally fail to accurately predict the ice content of high-altitude cirrus clouds in the tropics.[14] Given the warming effect of such clouds on the atmosphere, improperly estimating their ice content is a potentially serious shortcoming. A-Train measurements of cloud temperatures and ice and water-vapor content allow modelers to examine specific processes related to cirrus cloud formation in large-scale models. Hopefully, such investigations will lead to significant advances in our ability to represent those clouds, an important component of the climate system. More generally, the A-Train enables climatologists to determine quantitatively the relationships between a wide variety of cloud properties and the surrounding environment on scales of several to hundreds of kilometers.[15] Such studies can provide insights that ultimately serve to improve model simulations. A-Train measurements of ozone-depleting trace gases and polar stratospheric clouds also help modelers of stratospheric chemistry make quantitative assessments of polar ozone depletion[16] and evaluate models of polar processes affecting ozone recovery.

The future of constellation missions

The division of instruments among the satellites of the A-Train mitigates the problems inherent in complex multi-instrument payloads without compromising the sensors' ability to make simultaneous measurements. In the near future, at least one new satellite will join the train. Scheduled for launch in November of this year, *Glory* will extend the long-term record of total solar irradiance and will observe natural and anthropogenic aerosols. Japan's *Global Change Observation Mission–Water*, which will carry the successor to one of the microwave radiometers aboard *Aqua*, may join the train in 2012.

Of course, the A-Train cannot be maintained indefinitely. But its contributions to addressing questions about atmospheric composition and the integrated energy and water cycles offer a strong argument for adapting the constellation template to future missions with common themes.

In 2007 a National Research Council committee comprising experts from all areas of the scientific community issued its detailed decadal survey *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, in response to requests from NASA's Earth Science program, the National Oceanic and Atmospheric Administration, and the US Geological Survey to summarize Earth-observing needs in the next 20 years. The National Research Council report is an important road map that outlines and prioritizes 17 new space missions that will become the cornerstone of Earth observation. But the report fails to explicitly outline plans for coordinating future satellites, even though it advocates for several missions with common themes. As NASA and other space agencies plan the future of Earth observation, they should strongly consider adopting the A-Train paradigm, which, we believe, will maximize the scientific impact of their missions.

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The online version of this article includes a list of A-Train sensors and brief descriptions of their primary purposes.