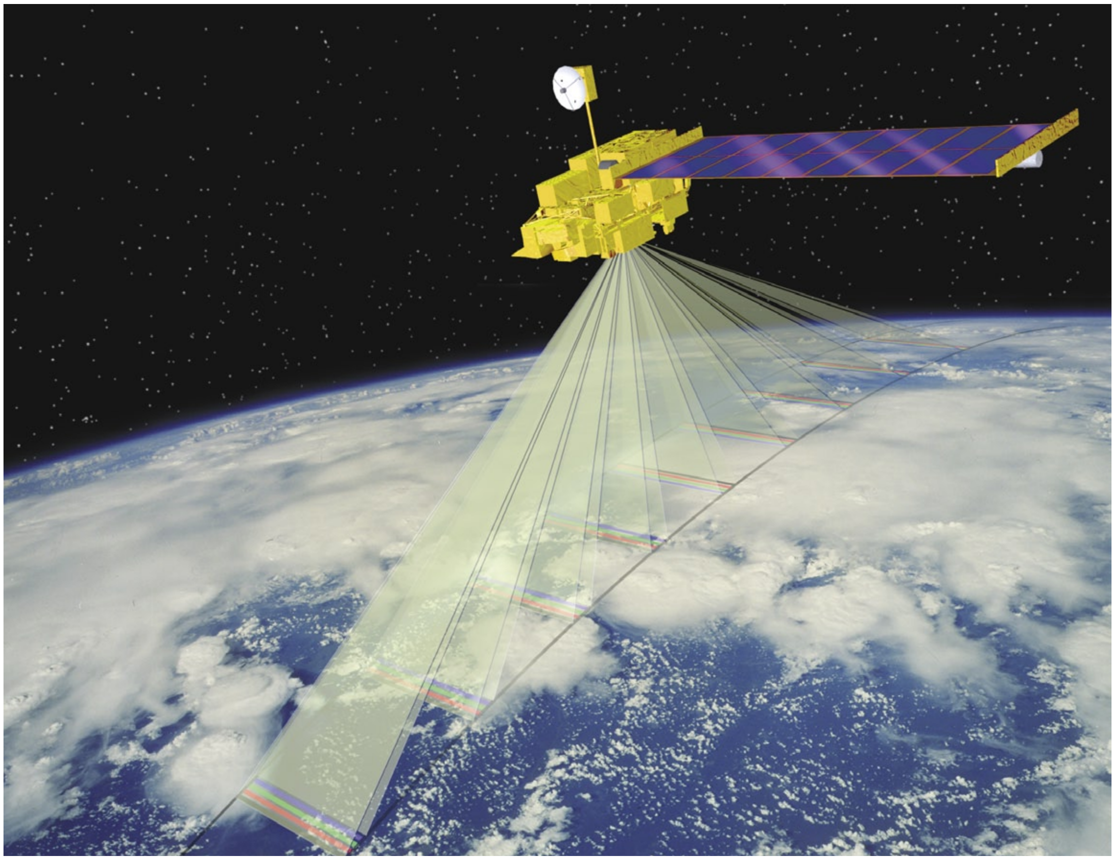
Our Atmosphere: The View from Above

by Eric J. Fetzer

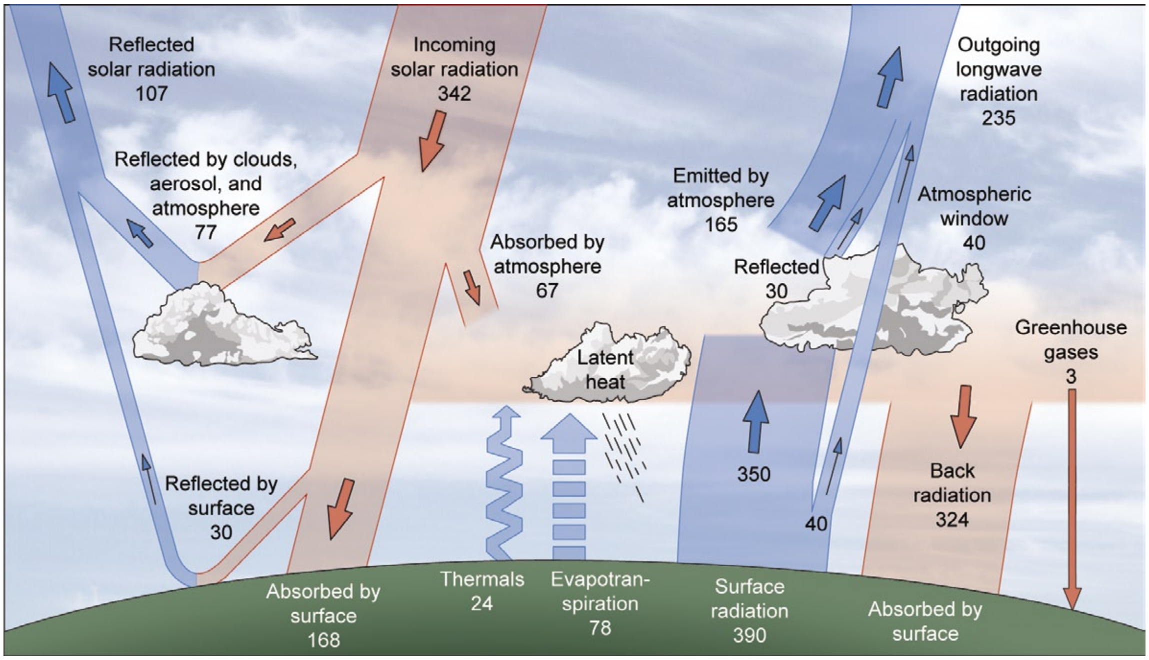


The Multi-angle Imaging SpectroRadiometer (MISR), built and managed by JPL, flies on the Terra satellite. MISR's nine attached cameras each point in a different direction, and each takes images in four different wavelengths. These images are used to track atmospheric smoke, dust, ash, and pollution, which play key roles in climate change.

This view from space is brought to you by several of the latest generation of satellite instruments viewing our atmosphere. Climate science is about simple concepts playing out in a very complex system. It has been said that the art of physics is judicious simplification; I would say that the art of atmospheric science is actually judicious complication. So what we can learn about this system using satellite observations? And, of course, why does all of this matter?

There are clearly some outstanding issues in the climate sciences. One is greenhouse gases, and their several attendant issues, among which is global warming—each of us in the United States alone produces several tons of carbon dioxide per year, contributing significantly to a greenhouse effect that has important implications. Pollution and dust also have an impact on climate, not to mention air quality. Then there is the granddaddy of all pollution problems, the Antarctic ozone hole. But I predict the big issue of this century will be how global warming affects future water supplies.

The climate cycle is a complicated system of components that absorb and reflect solar radiation. Around 342 watts per square meter (W/m²) of solar radiation enters Earth's atmosphere, and the same amount reradiates back from the planet, but this radiation takes many detours along the way. It can get trapped in clouds or reflected by clouds, absorbed by Earth's surface in some places and reflected in others. Each path taken must be tracked and understood in order to understand the entire system. Anthropogenic greenhouse gases, despite amounting to a measly three W/m² of the radiation budget, are an important factor in climate change.



The outstanding issues in the climate sciences primarily have to do with how the climate system maintains an energy balance. Into this balance are thrown complications like clouds, water vapor (which is actually the number one greenhouse gas), and pollution. These things, unfortunately, are all tied together, with no easy way to disentangle them. Like the legendary Gordian knot, they form an inextricable tangle with no ends. But, unlike Alexander the Great, who began his ascent to the throne of Asia by slicing the knot in half, we don't have a sword. We can't hack this knot into pieces, so we have to disentangle it very carefully through approaches like analysis, observation, and computer modeling—all of which are based to a large degree on satellite observation.

Let's begin our exploration of the atmosphere with a trip to your driveway. When you stand on a very hot driveway in the full sun, you feel intense heat on your skin, which happens to be a very good sensor of infrared radiation. You are feeling the very simplest case of radiative balance: sunlight comes in and infrared radiation goes out. The atmosphere behaves in a similar manner, conceptually. The sun heats Earth's surface at 342 watts per square meter. That's essentially one toaster for every three square meters, at a thousand watts per toaster. And there are about 342 watts per square meter, on average, reradiating back from the planet into the atmosphere. So there is a long-term balance between what goes in and what comes out.

Unlike in the driveway model, solar energy's many paths to the planet and back through the atmosphere are a little more complex. Clouds and Earth's surface can both reflect sunlight and absorb it. Snow is a very strong reflector, while bare dirt or sand absorbs solar energy. Water also absorbs almost all the sunlight that hits it. Some of this energy is reradiated as heat, which is visible from space as infrared radiation. Several of the instruments we work with at JPL "see" this infrared radiation. In tracing the various paths of solar energy, we face the complexity of the climate system, which involves variable reflectivity and reabsorption from clouds and Earth's surface, as well as a number of other effects going on inside the atmosphere. Understanding the atmospheric part of the climate system is all about understanding these internal exchanges.

Water vapor is a big player in this energy balance. We hear a lot about carbon dioxide and other anthropogenic gases as the important greenhouse gases, and they are definitely linked to our warming climate, but they don't have nearly as great an impact on climate as water vapor, a naturally occurring greenhouse gas. Clouds are even more important than water vapor. The presence of different types of clouds, some that lead to cooling and some to warming of the atmosphere, will probably have a much greater impact on climate change than the small but positive effects of carbon dioxide. The magnitude of the carbon dioxide–induced warming is reduced or amplified by cloud feedbacks. Because we don't know some basic things, like the actual distribution of different types of clouds globally, understanding these feedbacks is especially challenging.

Keep in mind that human-produced greenhouse gases amount to only a few percent at most of all these numbers coming in and going out of the atmosphere in a somewhat confusing way. To understand the climate system better, we need to understand how this small number, the amount of greenhouse gases in the atmosphere, can be so important in the face of these larger numbers.

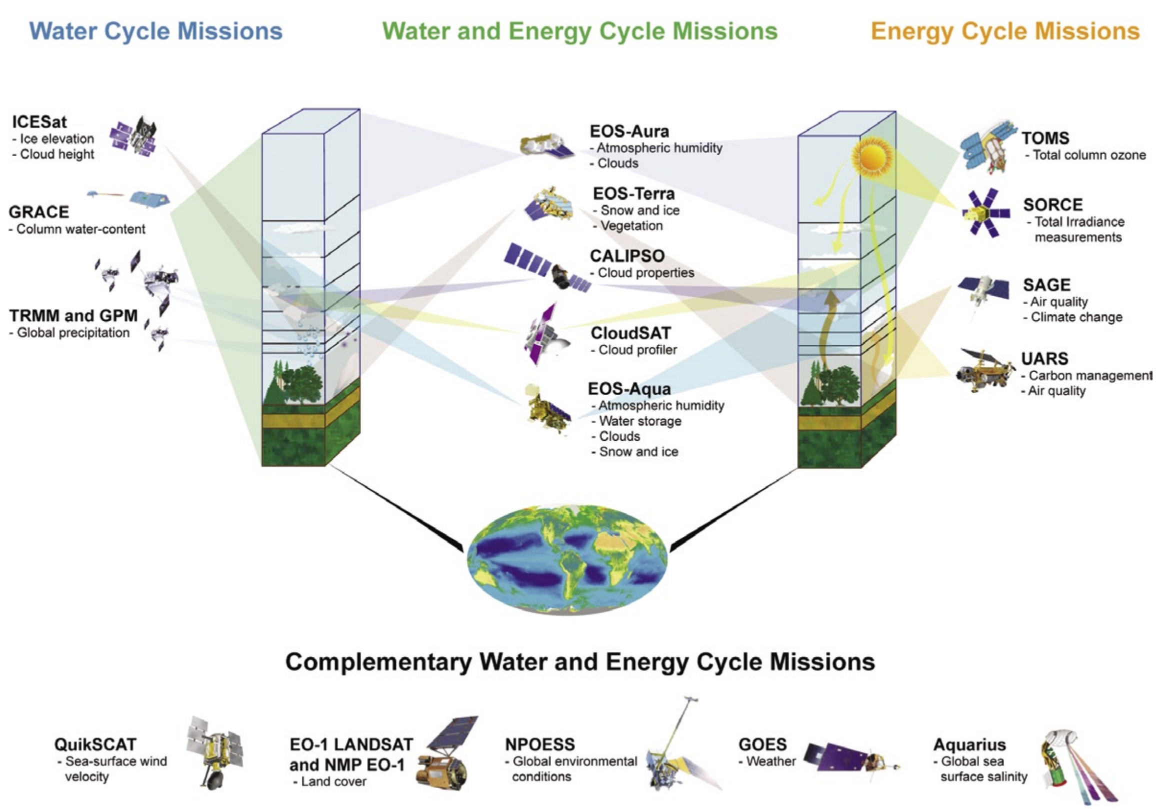
Finally, atmospheric motion is also critical to the whole picture of energy transport. Much of the year, Antarctica receives no sunlight, yet it radiates energy to space. That heat has to come from somewhere, and this is where the atmosphere and ocean come in. They take heat from the tropics and redistribute it to the poles and to higher latitudes. This redistribution of heat, in a broad sense, is the climate system.

You might think measuring thermal radiation from a piece of land is trivial, but this apparently trivial problem is something we still don't understand in detail. The world is a lot more complex than a driveway, and we don't fully understand the properties of everything that the sun shines on.

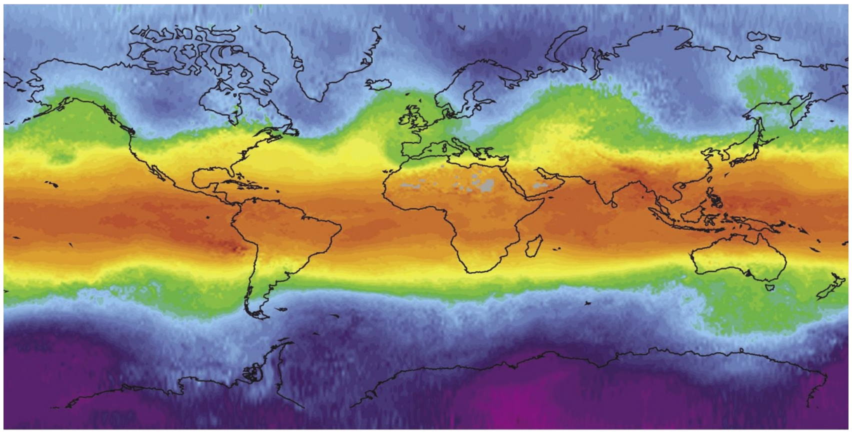
Why observe this all from space? Because we get near global coverage, with gobs of data pouring in. We have the potential to see detailed pictures of many processes. But there are challenges that come with this. Rather than directly observing many components of the atmosphere, we make inferences about them based on some prior understanding. For example, we don't actually observe temperatures from space, we infer them based on observations of radiation. Returning to the driveway example, we can't simply take a thermometer reading of the driveway's temperature from space. Instead, we measure the intensity of infrared radiation from the driveway, and then infer a temperature for it based on the known physical properties of the driveway. And there are parameters that might be fundamental to radiative balance that we can't observe from space, like back radiation from the atmosphere to the ground, so we have to infer these in other ways. There are also certain climate states that we can't observe. Very few instruments can observe deep into hurricanes, for instance.

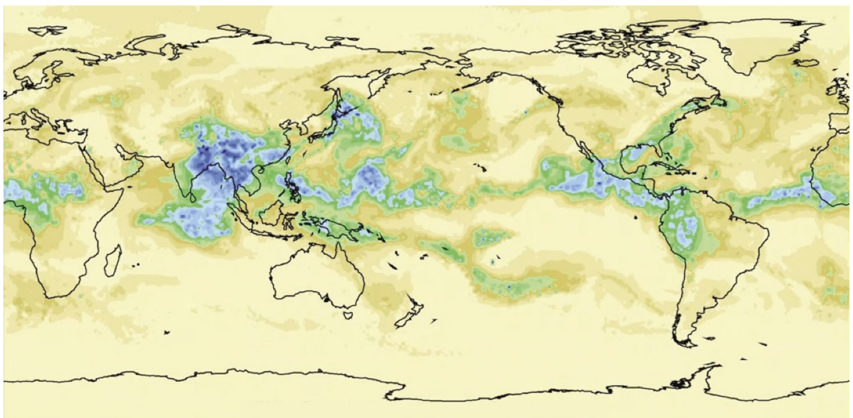
You might think measuring thermal radiation from a piece of land is trivial, but this apparently trivial problem is something we still don't understand in detail. The world is a lot more complex than a driveway, and we don't fully understand the properties of everything that the sun shines on. Furthermore, we don't understand the details of all the data we do have. Data is not information, and information is not knowledge. How do we transform data into information, and then use that information to gain insight into the atmosphere? Finally, once we get through the process of inferring from observations, we have to look at our inferences to make sure they make sense. Part of the job is knowing where and when those inferences could be wrong.

Much of the data that we analyze come from instruments carried by one or another of the satellites of NASA'a Earth Observing System, or EOS. All 17 satellites employed in EOS missions are devoted to making myriad observations related



NASA's Earth Observing System, or EOS, comprises 17 satellites launched periodically over the past two decades. Each satellite carries instruments designed to monitor various components that contribute to the climate cycle. The satellites follow either polar-orbiting or low-inclination tracks, repeating their observations regularly and thus improving our understanding of Earth as an integrated system over the long term.





Top: Temperature is distributed fairly smoothly at around five kilometers' altitude, ranging from hottest near the equator (reddish hues) to coldest near the poles (purple). People living in the midlatitudes experience winter storm systems that arise along the wavy front where hot air meets cold high in the atmosphere. This image shows an eight-day average temperature distribution in May 2004. Bottom: In contrast, water vapor in a layer from five to fifteen kilometers' altitude is unevenly distributed. The wettest places on Earth are above the tropics (as shown in blue), but moisture isn't spread evenly *throughout* the tropics. This image averages two days of data from late August 2004. Images by Stephanie Granger, JPL.

to Earth's water and energy cycles, and many of those instruments are built and operated by JPL. For example, we are constructing highly accurate temperature profiles of Earth's atmosphere from measurements made by the Atmospheric Infrared Sounder (AIRS), a JPL instrument launched on the Aqua satellite on May 4, 2002.

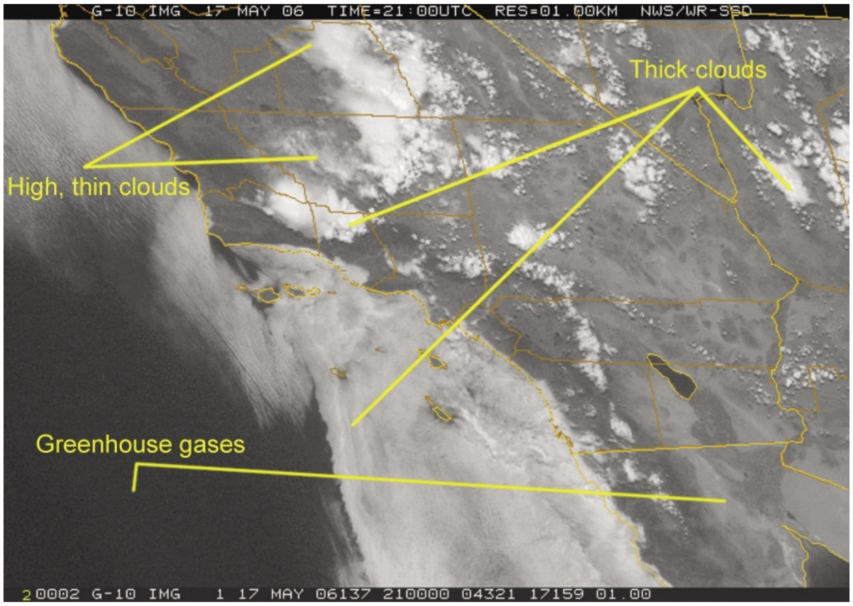
Let's continue our exploration of the atmosphere, with data from AIRS, by considering temperature distribution at a pressure of 500 hectopascals, or 500 millibars, which occurs some five kilometers above Earth's surface. Some things are expected: it's warm at the tropics and cold at the poles. But the interface between the cold polar air and the warm tropical air is wavy. Over the span of 11 months of temperature inferences, at some altitude well above the surface, waves of warm and cold air roll along this interface. We live in these rolling "waves" in the wintertime here in North America. These are the so-called midlatitude storm systems, and they are the mechanisms by which heat is transferred by the atmosphere from equatorial regions to the poles. The waves slosh along, generally from west to east, changing from day to day, which is why today's weather can be quite different from yesterday's weather. What these waves do at five kilometers' altitude is coupled to what we experience on the ground. It becomes clear, then, that the day-to-day view of global temperatures entails a lot more complexity than what we saw in the static view of radiative balance in the driveway model.

The next quantity we'll look at is water vapor, the fundamental greenhouse gas, which is also measured with the AIRS instrument. At roughly the same altitude of five kilometers and on up to 15 kilometers or so, the so-called upper tropospheric water vapor is distributed in a complex way. While temperature varies fairly smoothly from hot to cold across the globe, water vapor masses are scattered and disorderly, with filaments and blobs. Cloud distribution is even more spatially variable. As we saw earlier in the radiative balance example, these water vapor and cloud masses contribute to the energy balance of the planet. Upper tropospheric water vapor amounts, while small, are important in determining the radiative balance of cloud-free regions.

Although some of the wettest places on Earth are in the tropics, some of the driest parts of the upper troposphere are also there. So, while water vapor is generally more abundant in the tropics, this is not necessarily the case *throughout* the tropics. In the upper troposphere, as water vapor moves around, carrying temperature changes with it, it also changes its state to form clouds or ice. These changes add up to a poorly understood climatic system in one particular part of the atmosphere. But it is in the lower altitudes where much of the atmospheric water cycle is dictated, because most of the atmospheric water vapor lives here. There are other factors at play in the lower atmosphere, like surface evaporation, that help determine its water vapor abundance.

Into this already complicated scenario float the clouds. Water vapor, temperature, and clouds are all interrelated in the climate system: temperature depends on whether clouds are present, and clouds are present depending on the temperature and availability of water vapor.

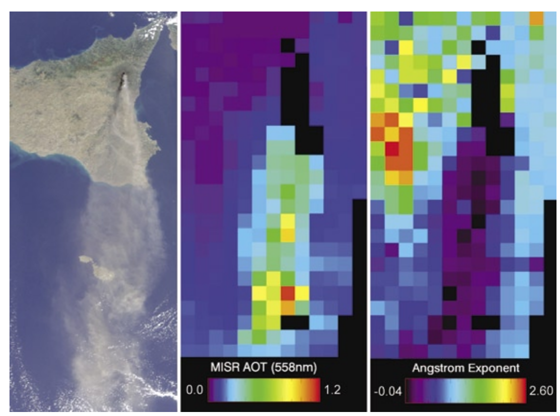
A typical May day in Southern California. This weather satellite image shows various kinds of clouds and a marine fog coming off the Pacific Ocean. These, along with greenhouse gases, play different roles in reflecting or trapping incoming solar radiation.



You may now be sensing the challenges of trying to understand clouds. Satellites are our best hope for doing this because they give us lots and lots of detailed information. However, complications arise in our understanding of the role of clouds in the climate system. Let's consider as an example a satellite photo from NOAA's Los Angeles forecast office, of weather in Southern California in May 2006. There were thunderstorms inland in northern Santa Barbara County and vicinity, and, along the coast, low-lying, thin fog known as the marine layer coming off the Pacific Ocean. This is not too atypical of Southern California in summer. High, thin clouds act as a thermal "blanket," transmitting sunlight but trapping heat radiating back from the ground. Thick clouds reflect sunlight from above back into space, thus helping to cool the surface. Low, thin clouds may be present, but they neither heat nor cool. And in regions with no clouds, greenhouse gases warm the planet. All of these factors, distributed across only a couple hundred miles, have to be taken into consideration in the radiative balance of this scene. Now consider the whole planet, which is a lot bigger than that!

Some other recent work, by senior research scientist Ralph Kahn at JPL and his colleagues, is focused on understanding aerosols, which are tiny particles suspended in the atmosphere. Desert dust, wildfire smoke, and volcanic ash are all aerosols, and their impact on surface and atmospheric temperatures make them an important factor affecting climate. Most aerosols actually cool the planet by blocking sunlight that would otherwise reach Earth's surface—for example, ash from the volcanic eruptions of El Chichon in 1982 and Mount Pinatubo in 1991 significantly cooled the planet for a year or two. Kahn heads a research team working with data from the Multi-angle Imaging SpectroRadiometer (MISR) instrument, which was built and managed by JPL and launched on December 18, 1999, on Terra, the flagship of EOS's advanced instrument-carrying satellites. The MISR instrument has nine attached cameras, each pointed in a different direction and each taking images in four different wavelengths, so it is set up, in part, to monitor the brightness, contrast, and color of sunlight reflected back to space by aerosols.

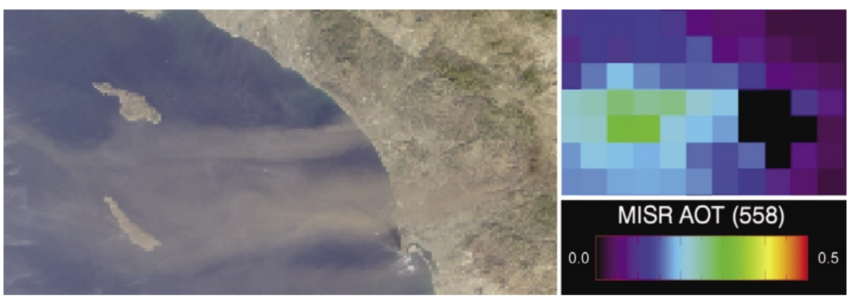
Looking at the ash cloud from the October 2002 eruption of Mount Etna, Kahn's team came up with a quantitative measure of aerosol optical thickness—or how well you can see through the particle cloud—and how that visibility varies with the wavelength of light. An image taken from directly above Mount Etna by one of MISR's cameras, at a resolution of 1.1 kilometers, is compared with a compilation of similar images from the other cameras. In the optical depth image, each pixel is 17.6 kilometers on a side, and color-coded by the difficulty of seeing through the aerosols in that region. The volcano itself is opaque, and parts of the plume have a high optical thickness. For reference, smoggy air typically has an optical depth of around 0.5 to 1.0, and it is impossible to discern most objects behind a haze that has



Ash erupted from volcanoes can significantly cool the planet by blocking sunlight from reaching Earth's surface. MISR images from the 2002 eruption of Mount Etna helped determine the aerosol optical thickness (AOT, middle panel), or how difficult it is to see through the ash plume. In the Angstrom exponent map (right panel), which shows the distribution of particle size, the ash plume is easily discerned.

an optical depth greater than three. Another property, the Angstrom exponent, relates the change in optical depth with wavelength to the particle's size. Generally, the larger the Angstrom exponent, the smaller the particle size, so something like an ash plume can be easily distinguished from background air particles. Combined with images that show the elevations of different materials, from sea level on up, optical depth and particle size calculations can help map the true distribution of aerosol amount and type in the atmosphere.

We can use MISR to quantify other sources of dust in the atmosphere, like desert dust or smoke from fires. In Southern California, the Santa Anas, which are dry, hot winds channeled out of the desert in winter, can play a significant role in moving dust through the atmosphere. Similar and larger dust plumes are generated in the dusty expanses of the Sahara and the Gobi deserts, from where they are blown out to sea and sometimes cross entire oceans. While volcanic ash in the upper atmosphere can cool the planet by blocking sunlight, dust in the lower atmosphere absorbs sunlight and reradiates it as heat. So pure dust in the air can become a significant component to local atmospheric heating. This is just one more thing we have to think about.



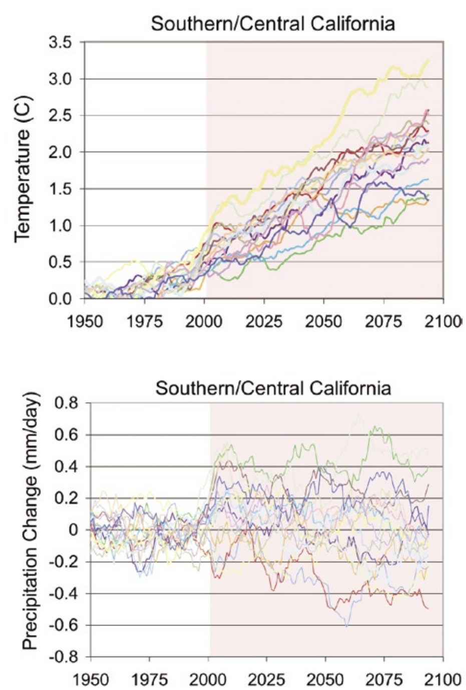
As opposed to ash in the upper atmosphere, dust in the lower atmosphere absorbs sunlight and can warm the atmosphere. These dust clouds off of Southern California are mapped using the optical depth determinations of the MISR instrument.

Why should we care about climate-related issues? The answer is simply that we need to know what is going to happen to the planet, because these issues affect everyone. Right now, though we don't have a detailed understanding of many climate processes, we do have many climate models, which come from computer predictions based on several variables. Those include equations of motion for the atmosphere, our best estimates of interactions of cloud particles with each other and with aerosols, and a description of how radiative balance is maintained. Seventeen climate models designed to predict the long-term temperature, whose outputs were analyzed specifically for Southern California and project through the year 2100, all show that we expect warming. Similar agreement is seen for most places on the planet. So why do we need to keep studying this question? Sure, there are some minority voices saying this is not true, but the overwhelming scientific consensus is that we will see global warming, and it is a consequence of anthropogenic greenhouse gases. This is acknowledged by everyone from Greenpeace to the Bush administration.

Global warming is a problem we will have to deal with, so the question becomes, "How does one deal with this?" The answer is critical to our future management of resources like water. If we look at forecasts of rainfall in Southern California, we see that our ability to make predictions diminishes rapidly. This is due mostly to the feedback between temperature, water vapor, and clouds. Because the atmosphere can hold more water as it warms, increasing temperatures may lead to more water vapor and even more warming. But there are many other feedback mechanisms potentially at work, some of which lead to cooling. As we saw earlier, low, thick clouds cool the planet by reflecting sunlight, even as other clouds warm by transmitting sunlight but blocking infrared radiation escaping the lower atmosphere.

The California climate models each treat cloud feedbacks and the associated water cycles slightly differently, leading to different long-term predictions of rainfall. So, as opposed to the consensus on global warming trends, there is wide disagreement about what will happen to the water cycle. Will the future bring more rainfall or less?

When considered on a global level, the impact of changes in precipitation could have dire consequences. Further drought appears likely in Africa and in the Middle East, where the climate is already fairly dry. Shrinking of mountain glaciers in the Himalayas could disrupt the water supply to the



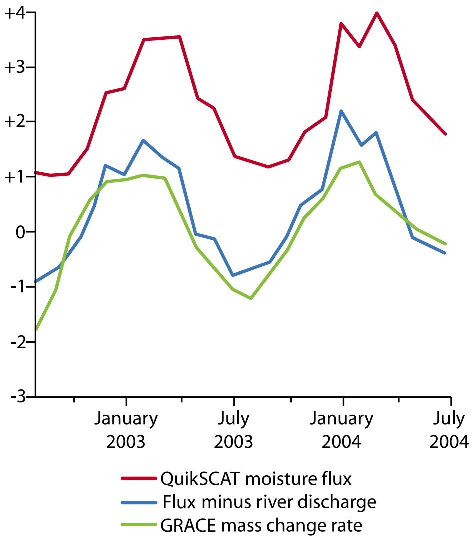
Despite our confidence in long-term climate models that predict warming for most places on Earth, predictions of precipitation are all over the place. As you might imagine, this has serious implications for future water supplies. Analyses by Duane Waliser, JPL.

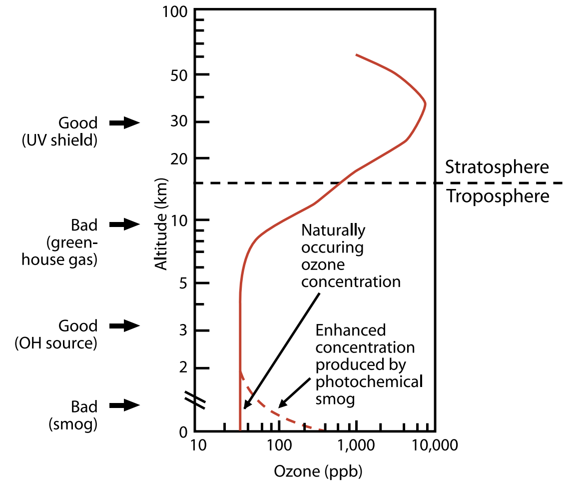
more than one billion people in India and China who depend on runoff from those mountains. The geopolitical implications of changes in the hydrologic cycle as a result of global warming are significant.

It is clear that atmospheric scientists need to understand the water cycle, and this understanding will primarily come from observation. Timothy Liu, a senior research scientist at JPL and leader of the NASA Ocean Surface Vector Wind Science team, uses space-based observations to study how surface winds distribute heat and water vapor between the ocean and the atmosphere. These observations are made with three more of the EOS satellites. The Quick Scatterometer (QuikSCAT), built by JPL, was launched in June 1999 to measure ocean surface winds. The Gravity Recovery and Climate Experiment (GRACE), which carries JPL instruments, measures changes in Earth's gravity field over time, including those caused by changes in groundwater storage on land. And, finally, the Tropical Rainfall Measuring Mission (TRMM) measures how much rain falls over the tropics and how much heat is released with it. The measurements made by these three satellites quantify the influx of water through precipitation, and the distribution of water by winds. These quantities are then compared to the amount of water lost from the oceans by evaporation and the amount of water leaving the continents and flowing into the oceans from rivers (based on years of data collected by ground-based river gauges). Liu's studies of South America recently established the first reliable space-based water budget for a whole continent. It shows that the total water budget of South America (gain by precipitation minus loss by rivers) matches both in magnitude and in phase the mass change from gravitational pull measured by GRACE. But this is only a beginning. We would like to understand the water budget of the entire planet, down to individual river basins.

Two final climate-related issues worth mentioning are air quality and the ozone hole. We still have widespread problems with pollution, even though air quality in Los Angeles has greatly improved since 30 or 40 years ago, in part through work by people at Caltech. But many large developing-world cities have air pollution issues that make ours pale in comparison. The pollution in these cities is a consequence of burning fossil fuels for heating, cooking, transportation, and industry. Also, the burning of forest and grassland for agriculture, and overall deforestation in general, are other persistent issues related to global warming. This burning of what we call "biomass" releases ozone, whose role shifts between good and bad depending on how far it lies above Earth's surface.

Ozone is beneficial in the upper atmospheric layer called the stratosphere, which extends from about 10 kilometers to about 50 kilometers above Earth's surface. In its most concentrated layer, 20 to 25 kilometers above Earth's surface, stratospheric ozone protects us from ultraviolet rays, which cause skin cancer. Descending into the lower atmosphere, called the troposphere, at 10 kilometers above the surface, ozone is a greenhouse gas, contributing to global warming. Then at three kilometers above Earth's surface, ozone is good again, helping to remove many chemical pollutants. But at ground level, ozone in the air we breathe is harmful, causing premature lung aging.





Ozone plays roles that alternate between good and bad (for us!) at different levels of the atmosphere. Ozone levels are in parts per billion.

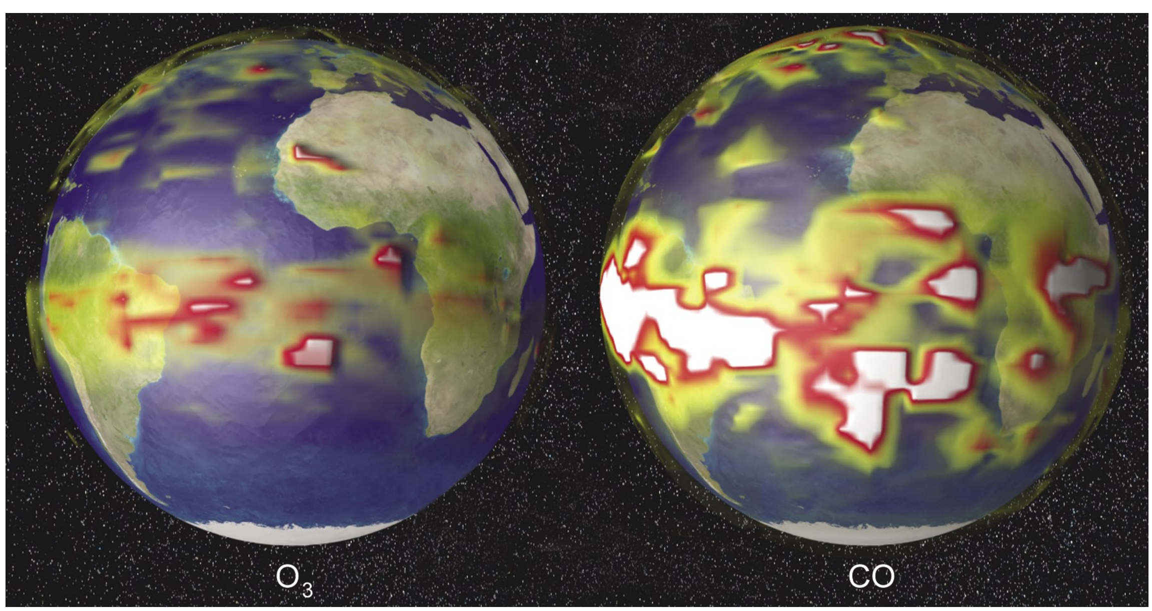
Above: Space-based measurements of the moisture flux over South America (red line) are tracked from space by the Quick Scatterometer. From these measurements is subtracted the water loss from the continent measured with ground-based river guages. The resulting water balance (blue line) matches both in amplitude and phase the mass changes (green line) measured from space by the Gravity Recovery and Climate Experiment (GRACE).

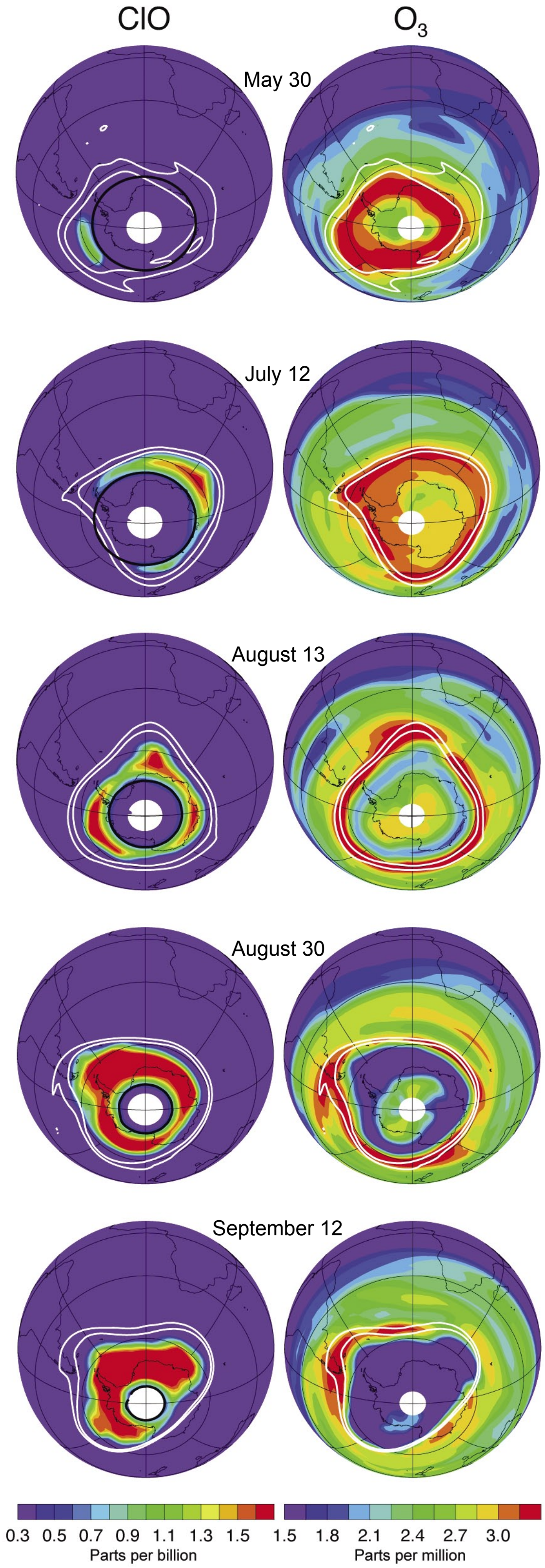
If we look at the presence of carbon monoxide and ozone as measured by the Tropospheric Emission Spectrometer (TES)—launched on July 15, 2004, on the EOS satellite Aura—we see that these gases appear and disappear over time. The images from Aura show that carbon monoxide is abundant in our atmosphere, and yes, that is the carbon monoxide that kills people when they don't ventilate their heaters properly. It is created by incomplete burning of vegetation. People in the tropics commonly burn grasslands in the dry season before summer rains begin, to improve forage. Ozone is created in this process as well, both by burning and by chemical processes in polluted air.

A year of TES data shows that Africa and South America are the major sources of these gases during the burning season. Atmospheric processes then pump ozone and carbon monoxide from these regions into the sky over the southern Atlantic Ocean. There is also some carbon monoxide and ozone in the Northern Hemisphere, due in most part to low pollution emission standards in China and Eastern Europe. As the year progresses toward winter, higher and higher levels of carbon monoxide and ozone appear in the high northern latitudes, because people heat their homes with fossil fuels, primarily coal. Incidentally, while big SUVs contribute some greenhouse gases, most are emitted through home heating.

Some of the most interesting atmospheric chemistry data coming from space are from JPL's Microwave Limb Sounder (also on Aura), which remotely senses atmospheric gases, temperature, pressure, and cloud ice. In a view of the globe centered on

Space-based measurements by the Tropospheric Emission Spectrometer (TES) show that Africa and South America are major contributors of the ozone (O_3) and carbon monoxide (CO) that then blow across the southern Atlantic Ocean from June–September. Relative concentrations range from lows shown in black, to intermediate values in yellow, to highs shown in red–white.





Antarctica, winter 2005. As chlorine monoxide (ClO, left column) builds up from early July to mid-September, ozone (O_3) disappears in the atmosphere 20 kilometers above Antarctica. In the darkness of polar night in the South Pole (the region *inside* the heavy black circle), clouds of frozen nitric acid host reactions that activate chlorine as soon as sunlight returns. Increasing sunlight as winter progresses leads to a increasing ClO abundances and greater destruction of ozone, until mid- to late September, when the icy clouds disappear. Descending air in the winter polar vortex (the pair of heavy white lines), a wind tunnel that isolates a region above the Antarctic through the winter (May-September), also helps replenish lower-altitude ozone from higher abundances above. After ozone reaches its minimum in mid-September, the vortex starts to shrink and eventually breaks down, and chunks of the "ozone hole" float northward. Maps of data from the Microwave Limb Sounder (MLS) by Michelle Santee, JPL.

Antarctica, we can track temperature, nitric acid, hydrogen chloride, and chlorine monoxide, which all play a role in ozone chemistry through the year. From this data, provided by principal scientist Michelle Santee (MS '89, PhD '93) of JPL's Microwave Atmospheric Science Element, we see a rather complex chemistry that is fairly easy to interpret. I say "easy" with two caveats. First, it took years for the mechanisms at play in ozone destruction to be identified and understood. Second, the loss of ozone is still only easy to quantify in the Antarctic; the dynamics of ozone is much more complicated in the Arctic, because several competing factors there compensate for the chemical destruction of ozone.

The disappearance of ozone begins with the release of chlorine from chlorofluorocarbons, or CFCs, in the presence of sunlight. (That chlorine, by the way, comes from the CFCs that we all used back in the 1950s–1970s. While generally extremely long-lived, CFCs are broken down by intense ultraviolet light in the stratosphere. Many CFCs are still floating around up there, and they continue to be released today from countries where they are not banned.) Chlorine is anathema as far as ozone goes: a single atom of it destroys ozone and survives, going on to destroy many thousands more ozone molecules before being neutralized by some other reaction.

The chlorine released from CFCs becomes destructive only after it is activated; this activation begins in May on the surfaces of nitric acid particles that condense to form clouds in the very cold, early winter stratosphere over Antarctica. Early May is also polar night at the South Pole, so full-time darkness reigns. The reaction of activated chlorine with ozone begins only when sunlight returns to the Antarctic in July. These reactions create chlorine monoxide, which is the smoking gun signifying the destruction of ozone. The series of globes shown at left track the demise of the ozone and the rise of chlorine monoxide at 20 kilometers' altitude, and you can see that there is no chlorine monoxide in the polar night. So the ozone is fairly safe in mid-May, in the absence of sunlight, especially as it is being replenished in the lower stratosphere by descending winds from the upper stratosphere, where abundances are higher.

But as the sun returns in July, destruction eventually overcomes replenishment, and we start to see the ozone values in the lower stratosphere decline. The ozone loss accelerates as winter progresses, sunlight increases daily, and more and more activated chlorine reacts with ozone. By mid-September, chlorine monoxide is at its highest, and a region the size of the entire Antarctic continent is almost completely depleted of ozone. This is what we call the "ozone hole." (By the end of September, the Antarctic air is too warm to host the icy clouds, and chlorine monoxide disappears.)

Fortunately for us, the deepening and widening ozone hole is kept confined to a region over the Antarctic by the "polar vortex," a region of air isolated from its surroundings by strong encircling winds. Until late spring, that is, when the vortex begins to break up, and chunks of the hole split off and float away to places like southern South America, New Zealand, and Australia. New Zealanders, as a result, are very concerned about their increased skin cancer risk. By late December, the ozone hole has vanished, and everything gets reset until the austral fall, when in the darkness of polar night the temperatures drop again, another winter polar vortex spins up, and the whole process starts all over again.

Our challenges in understanding the climate cycle have just begun. We need to integrate all our observations in some meaningful way. There are a lot of things we do not understand about how the climate system works. For example, while we now understand the mechanisms forming the Antarctic ozone hole, and treaties since the 1980s have sought to diminish ozone loss, global warming is a far more complex issue. Furthermore, a lack of complete observations leaves the water cycle not fully understood, especially over land. Our eventual understanding will help us address issues of water supply. There are also persistent questions about how clouds and aerosols cool the planet, and even about how both those quantities interact. All of these open questions carry serious implications for our future quality of life.

What happens to the climate because of widespread burning of cow dung for fuel in India, for instance? The resulting soot particles can act as condensation nuclei for clouds, which reflect sunlight and actually cool the planet. In this case, aerosols indirectly cool the planet, and appear to counteract some of the anthropogenic warming caused by increased carbon dioxide and other greenhouse gases. We need to understand exactly how this happens. Some people have pointed out that global warming, ironically, can be counteracted by dirty air.

But could that counteract the classic feedback mechanism at work in global warming: rising temperatures leading to increasing water vapor, which will lead to a heightened greenhouse effect? The magnitude of that effect is still not understood, and there are many, many other mechanisms that we need to understand in order to make reliable predictions in the face of climate change. The real challenge lies in improving climate forecasts, and I think the societal benefit of this should be apparent to all of us. □

Eric Fetzer arrived at the Jet Propulsion Laboratory in 1991 as a postdoc, and is now a senior member of the technical staff. He earned a bachelor's degree in physics from the University of California, Berkeley, and a PhD in atmospheric science from the University of Colorado, Boulder, where he studied waves in Earth's stratosphere. He has worked since 1994 on the Atmospheric Infra-Red Sounder (AIRS) instrument, and also leads an effort to characterize water vapor and clouds using several other satellite instruments. His group won a NASA Group Achievement Award in 2004. In his spare time, Eric gets in loads of trouble while hiking, mountain biking, and rock climbing with Caltech alumni.

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Below: Clouds of frozen nitric acid, sulfuric acid, and water vapor form the substrates for chemical reactions that activate chlorine to destroy ozone. These clouds form when temperatures drop below -88°C, and are present usually between the end of May and end of September over Antarctica. Photograph over Iceland by Mark Schoeberl, NASA.