SATELLITES

Research (Atmospheric Science)

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Introduction

0363-P0005 The atmosphere changes chemically and physically on widely varying time scales – ranging from minutes to decades – and is therefore a challenge to measure precisely over the entire globe. But with the National Aeronautics and Space Administration's (NASA) 1960 launch of the Television Infrared Observation Satellite (TIROS), Earth scientists began a new mission to observe large-scale weather patterns from space. In the late 1970s, their mission expanded to include global-scale measurements that would help them understand the causes and effects of longer-term climate change. NASA and its affiliated agencies and research institutions collaborated to develop a series of research satellites that have enabled the testing of new remote sensing technologies that in turn have advanced scientific understanding of both chemical and physical changes in the atmosphere. ("Remote sensing" involves the use of devices other than our eyes to observe or measure things from a distance without disturbing the intervening medium.) The goal is to examine our world comprehensively to determine what dynamics drive Earth's climate system and how climate change both affects our environment and is affected by it.

0363-P0010 Depending upon their measurement objectives, research satellites primarily fly in one of two orbits: (1) a near-polar, Sun-synchronous orbit to allow their sensors to observe the entire globe at the same solar time each day, or (2) a mid-inclination, precessing orbit to focus their sensors on the equator and lower latitudes where the observations are made at different times of day to better sample time-varying phenomena such as clouds. Some polar orbiting satellite sensors can observe any given place on the globe as often as every day, thus collecting data with high temporal (time) resolution. Other satellite sensors view any given place as infrequently as once every 16 days, thus having relatively low temporal resolution for a satellite sensor, but still far surpassing our ability to make these same measurements with surface-based or aircraft sensors. Satellite sensors with high spatial resolution (15 meters per pixel) can discern objects in the atmosphere or on the surface as small as, say, a football field, thus providing high spatial resolution. Other satellite sensors that are designed to measure continental and global-scale dynamics typically have only moderate (500 m per pixel) to low (20 km per pixel) spatial resolution. Satellite sensors carry specially designed detectors that are particularly sensitive to certain wavelengths of the electromagnetic spectrum, called spectral bands. The more precisely a remote sensor can measure narrow bands of radiant energy, and the greater the number of these discrete bands it can measure, the higher is its spectral resolution. The atmosphere interacts with solar radiation much like a venetian blind – selectively absorbing and reflecting certain wavelengths of solar energy while allowing others to pass through. Satellite remote sensors are designed to be particularly sensitive to those wavelengths that can be reflected or emitted back up through the atmosphere to space, thus enabling them to make their measurements.

Earth-orbiting remote sensors provide the best 0363-P0015
means of collecting the data needed in research because they can measure things on scales of time and space that otherwise would not be possible. Moreover, satellite sensors not only observe wavelengths of visible light; they also precisely measure wavelengths of radiant energy that the eye cannot see, such as microwaves, ultraviolet rays, or infrared light. If it is known how certain objects (like cirrus clouds or windblown dust) typically absorb, reflect, and emit particular wavelengths of radiant energy, then by using satellite sensors to precisely measure those specific bands of the electromagnetic spectrum, a lot can be learnt about the Earth's atmosphere and surface. Remote sensors allow us to observe and quantify key climate and environmental vital signs such as temperature, ozone concentrations, carbon

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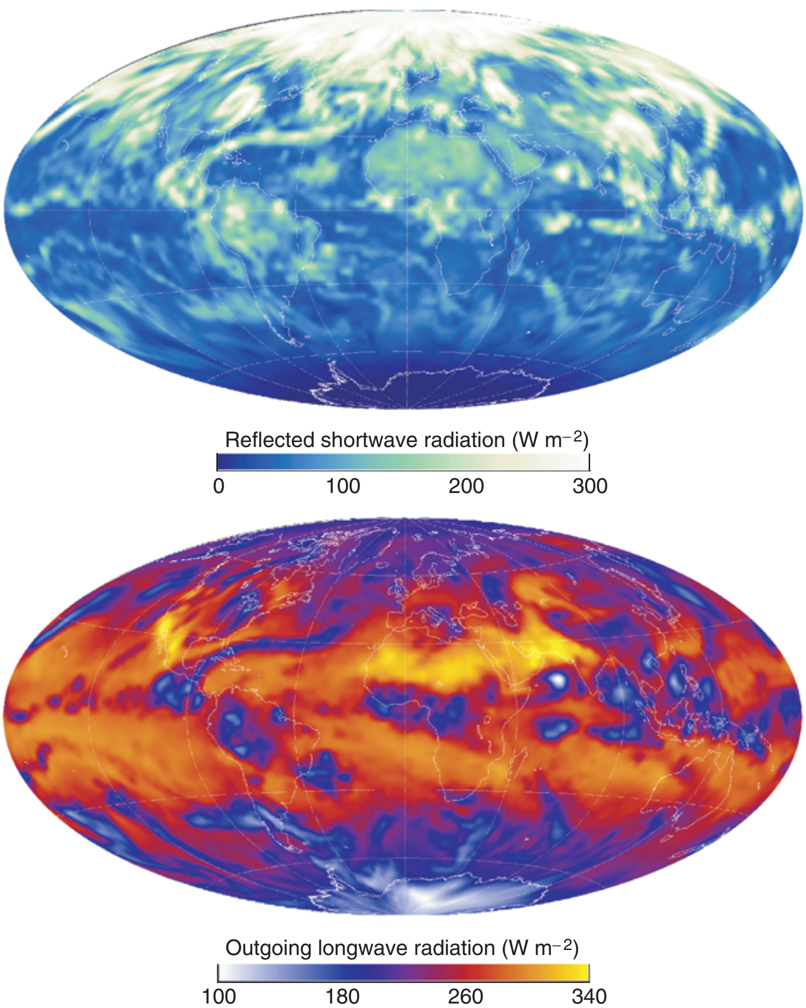
monoxide, and other pollutants, water vapor and other greenhouse gases, cloud types and total cloud cover, aerosol types and concentrations, radiant energy fluxes, and many more.

Balancing Earth's Radiant Energy Budget

0363-P0020 Climate is defined as the average state of the atmosphere, hydrosphere, and land over a given time. Thus, measurements of radiant energy within Earth's atmosphere are at the heart of the climate change discussion. How climate changes is related directly to how the planet balances the amount of incoming sunlight with outgoing radiant energy. The measurement of all incoming and outgoing energy provides a sort of ledger of all the physical motions and interactions of our world's climate system, showing whether, over the course of a year and over the entire globe, the Earth's total energy budget is in balance, or not, and if not, whether it is heating up or cooling down. So if we are to understand climate and accurately predict future climate change, then we must determine what drives the changes within the Earth's radiation balance (**Figure 1**).

In 1978, NASA launched its Nimbus-7 satellite 0363-P0025
carrying a new sensor, called the Earth Radiation Budget (ERB) experiment, designed to measure direct solar irradiance, reflected short-wave radiation (visible light), and emitted long-wave radiation (heat) every day over the entire Earth. This was the first space-based sensor capable of self-calibrating so that its total solar irradiance measurements were accurate to within ±0.5%. The Nimbus-7 ERB collected 9 years of global-scale data, upon which long-term climate



0363-F0001 **Figure 1** Global reflected shortwave radiation and emitted longwave radiation escaping the top of Earth's atmosphere, measured by CERES on 25 May 2001.

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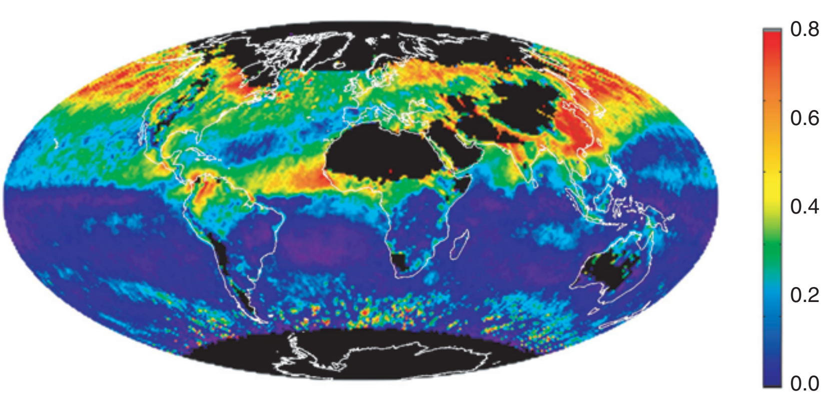
studies were began. In the interest of extending the ERB data set and improving upon its measurement capabilities, NASA launched three more Earth Radiation Budget Experiments (renamed ERBE) in the 1980s.

0363-P0030 In addition to total solar irradiance, ERBE measured the reflected solar and emitted thermal radiation from the Earth – atmosphere – ocean system. These observations revealed that over the course of a year the global radiation budget is in balance – the Earth reflects and emits roughly the same amount of energy back into space that it receives from the Sun. The data showed also that the average annual, global contribution by clouds is that they reflect $17\,\mathrm{W\,m^{-2}}$ more short-wave energy (visible light) than they trap as long-wave energy (heat). Yet, owing to calibration uncertainties, deficiencies in ERBE's sampling method, and the limitations of existing angular dependence models, there still exists a significant uncertainty (about $\pm 5\,\mathrm{W\,m^{-2}}$) regarding our understanding of Earth's radiation budget. Part of this uncertainty lies in our limited knowledge of the spatial distribution of clouds as well as the optical properties of these clouds over time. Moreover, we cannot be sure how the distribution and optical properties of clouds will change over time. The endeavor to address these issues began with the 1997 launch of the Clouds and the Earth's Radiant Energy System (CERES) sensor aboard the joint NASA/NASDA Tropical Rainfall Measuring Mission (TRMM) satellite. Twin CERES instruments were also launched aboard NASA's Terra satellite in December 1999, and the pair will again fly aboard NASA's Aqua satellite launched in early 2002. Many of the sampling and accuracy limitations on ERBE were addressed in the design of CERES so that it could meet the same measurement objectives as those for ERBE but with better than twice the former sensor's accuracy. Ultimately, it is anticipated that CERES will not only extend the ERBE data set but will also provide the first long-term global measurements of the radiative fluxes within the Earth's atmosphere that will help us more accurately account for the effects of aerosols and clouds on climate.

Dust in the Wind

0363-P0035 Aerosols are tiny particles suspended in the air (mostly in the troposphere). Some come from natural sources, such as volcanic eruptions, dust storms, forest and grassland fires, living vegetation, and sea spray. About 11% of the total emitted aerosols in our atmosphere come from human activities, such as the burning of vegetation and fossil fuels and changing the natural land surface cover, which again leads to windblown dust. Yet human-produced aerosols account for about half of the total effect of all aerosols on incoming sunlight. From a satellite's perspective, aerosols raise the Earth's albedo, or make it appear brighter, by scattering and reflecting sunlight back to space. The overall effect of these tiny particles is to cool the surface by absorbing and reflecting incoming solar radiation. They also serve as cloud condensation nuclei, or "seeds" for cloud formation, which again helps to cool the surface. In terms of their net influence on global climate, for scientists aerosols represent the greatest subject of uncertainty. Yet computer climate models estimate that over the last century human-produced aerosols have offset global warming due to greenhouse gases by about 40% (**Figure 2**).

0363-P0040 Through the 1980s and most of the 1990s, the NOAA Advanced Very High-Resolution Radiometer (AVHRR) was the most frequently used satellite sensor for measuring aerosol optical thickness. (Aerosol optical thickness is a measure of how much sunlight airborne particles prevent from traveling through a column of atmosphere.) However, AVHRR can only



0363-F0002 **Figure 2** Global aerosol optical thickness measured by MODIS in April 2001.

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make such measurements over the ocean, as the sensor requires a relatively uniform and dark-colored background. Because TOMS is particularly sensitive to absorbing aerosols, over both land and ocean, this sensor has also been widely used to measure aerosol optical thickness. In April 1991, the European Space Agency launched a new type of multi-angle sensor, called the Along Track Scanning Radiometer (ATSR), aboard their first European Remote Sensing Satellite (ERS-1). The ATSR makes aerosol optical thickness measurements by remotely sensing visible and near-infrared wavelengths at nadir and oblique forward scan angles (both within a 2-minute interval). A modified version of the sensor, called the Advanced Along Track Scanning Radiometer (AATSR), was launched in 1995 aboard ERS-2. While data from neither of these missions have yet been used to produce global-scale aerosol measurements, this should be possible.

0363-P0045 In 1996, Japan launched the first in its series of Advanced Earth Observation Satellites (ADEOS) satellites, which carried a payload of two sensors – the Polarization and Directionality of the Earth's Reflectances (POLDER) sensor, contributed by the French Space Agency, and the Ocean Color and Temperature Scanner (OCTS), provided by NASDA. Both sensors can retrieve aerosol measurements, but POLDER was the first satellite sensor designed specifically to measure aerosols, and it can make its measurements over both land and ocean. The sensor observes Earth targets from 12 directions that enable measurements of the bidirectionality and polarization of solar radiation reflected from within the atmosphere. Unfortunately, owing to its solar panel failing, the ADEOS mission ended prematurely after only 8 months in orbit.

0363-P0050 Three sensors aboard NASA's Terra satellite are particularly well suited for studying the effects of aerosols on climate: CERES, MISR, and MODIS. The Global Imager (GLI) planned for launch aboard ADEOS II offers aerosol measurement capabilities similar to those of MODIS. Both these sensors have the capacity to measure not only aerosol optical thickness but also the sizes of aerosol particles over both ocean and land. Particle size is an indicator of the source of the aerosol particles and helps scientists distinguish aerosols of natural origin from those that are man-made. Moreover, with its nine different look angles, MISR is ideally designed to quantify the reflective properties. Again, CERES complements MODIS and MISR by providing measurements of the short-wave radiation that aerosols reflect back into space. Together, these sensors are providing new insights into the roles of clouds and aerosols in Earth's total energy budget.

Abstract Art or Arbiters of Energy?

More than just the idle stuff of daydreams, clouds help 0363-P0055
control the flow of radiant energy around our world. Clouds are plentiful and widespread throughout Earth's atmosphere – covering up to 75% of our planet at any given time – so they play a dominant role in determining how much sunlight reaches the surface, how much is reflected back into space, how and where warmth is spread around the globe, and how much heat escapes from the surface and atmosphere back into space. Clouds are also highly variable. Clouds' myriad variations through time and space make them one of the greatest areas of uncertainty in the understanding and prediction of climate change. In short, they play a central role in the world climate system. Whereas thick, low-level stratocumulus clouds cool the Earth's surface by reflecting incoming solar radiation, thin, high-level cirrus clouds exert a warming influence by allowing sunlight to pass through but then trapping the heat emitted by the surface. The question of whether warming or cooling has the greater effect over time has been answered only relatively recently. From ERBE satellite data collected in the 1980s, coupled with aircraft and surface-based measurements, it has been demonstrated that, globally, clouds cool the surface more than they warm it. So great is the cooling effect that it is as if clouds remove the heat of a 60-watt light bulb from every 2- meter square of the Earth's surface. But will they continue to cool our planet over the next century if a greenhouse-gas-driven global warming scenario comes to pass? Or even, could the type and distribution of clouds change so that they primarily exert a warming influence? (**Figure** 3)

Two new sensors flying aboard NASA's Terra 0363-P0060
satellite, launched in December 1999, are designed to help scientists answer these questions. The Moderate-resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging Spectroradiometer (MISR) give scientists new capabilities for measuring the structure and composition of clouds. MODIS observes the entire Earth almost every day in 36 spectral bands, ranging from visible to thermal infrared wavelengths. With spectral and spatial resolutions superior to that of AVHRR (its heritage sensor), MODIS can measure a wide suite of clouds' physical and radiative properties. Specifically, MODIS can determine whether a cloud is composed of ice or water particles (or some combination of the two), it can measure the effective radius of the particles within a cloud, it can observe how much (or little) sunlight passes through a cloud, and it can measure the temperature and altitude of cloud tops. Moreover, with its unique 1.37 μm channel, MODIS observes

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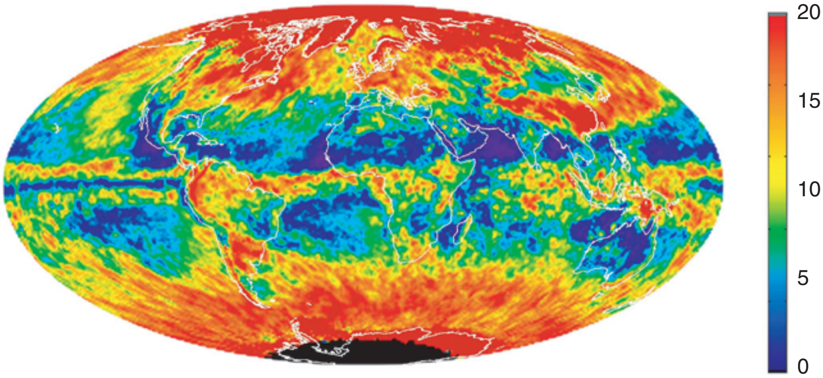

0363-F0003 **Figure 3** Global cloud optical thickness measured by MODIS in April 2001.

thin cirrus clouds with unprecedented sensitivity. This channel not only enables scientists to quantify the impact of cirrus clouds on the radiation balance, but also permits image analysts to "correct" for the presence of cirrus in remote-sensing scenes used to examine surface or lower-level features.

0363-P0065 Complementing MODIS, the MISR instrument "sees" the Earth simultaneously in red, green, blue, and near-infrared wavelengths at 9 different angles – at 4 progressively more oblique angles ahead of Terra, 4 angles aft of the satellite, and 1 at nadir. Because it measures any given scene from multiple angles, MISR is ideally designed to help scientists better understand how clouds interact with radiant energy as a function of both their structure and their type. CERES complements MODIS and MISR by providing measurements of the short-wave and long-wave radiant energy that clouds reflect and emit back into space.

0363-P0070 ESA's next-generation satellite missions for comprehensively examining Earth's climate system began with the November 2001 launch of its first Environmental Satellite (Envisat). Similar to MODIS in the scope of its research applications, Envisat carries the Medium-Resolution Imaging Spectrometer (MERIS). Like Terra's MODIS, MERIS has a wide viewing swath (1500 km), with a morning equatorial crossing, and it can see the entire Earth within every 3 days. Scientists are using its data to derive cloud cover, cloud altitude, water vapor, and aerosol properties. Unlike MODIS (which uses a cross-track scan mirror), MERIS is a push-broom scanner based upon Charge-Coupled Device (CCD) technologies with gains and offset settings that can be optimized for observing specific targets. This is a similar technology to that used by MISR.

Serendipity and Stratospheric Ozone

0363-P0075 In the early 1970s, as Earth scientists intensified their studies into the possible causes and effects of global warming, one group of man-made gases in particular elicited the attention of scientists – the chlorofluorocarbons (CFCs). Increasingly, CFCs were being used by industrial nations in the production of a variety of commercial products (e.g., refrigerants, aerosol sprays). The concern is twofold: CFCs are up to 200 times more efficient than carbon dioxide at trapping heat in the Earth's atmosphere, and they tend to remain in the atmosphere up to 120 years once released. Then, in 1974, two scientists wrote of a new concern that CFCs could potentially reduce levels of ozone in the stratosphere, the layer of atmosphere from 10 to 50 km in altitude. In 1975 the US Congress asked NASA to develop a "comprehensive program of research, technology, and monitoring of phenomena of the upper atmosphere". In particular, Congress's intent was to ascertain the "health" of the ozone layer (**Figure 4**).

So, in addition to ERB, in 1978 Nimbus-7 carried 0363-P0080
two other new NASA sensors designed to measure the total amount of ozone in a given column of atmosphere over the entire globe – the Solar Backscatter Ultraviolet (SBUV) instrument and the Total Ozone Mapping Spectrometer (TOMS). Sensitive to radiant energy in the ultraviolet region of the spectrum, these sensors took advantage of the fact that molecules and aerosol particles reflect certain wavelengths of ultraviolet rays while ozone absorbs others at different levels in the atmosphere. By analyzing the amount of ultraviolet energy reflected back up to the spacecraft, researchers could produce profiles of how thick or thin the ozone was at different altitudes and locations. Ironically, it wasn't until October 1985 that a British team of scientists found a significant reduction in ozone over Halley Bay, Antarctica. Using a ground-based Dobson ozone spectrophotometer, the team found that the amount of stratospheric ozone there was about 40% less than it had been the previous year. Their finding stunned the science community because it had been expecting anthropogenic ozone depletion

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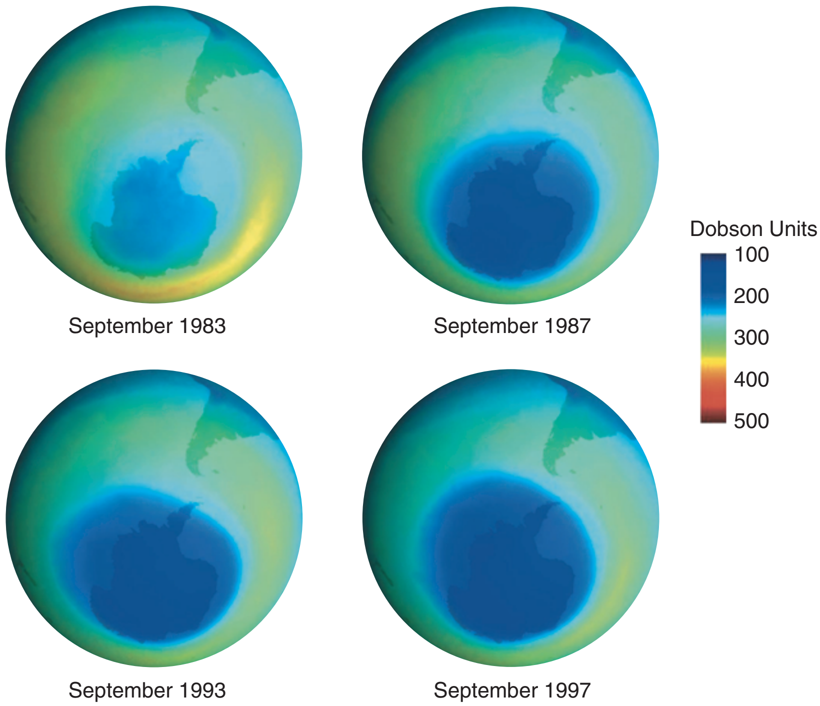

0363-F0004 **Figure 4** Total ozone content from TOMS in the Southern Hemisphere in September during the years 1983, 1987, 1993, and 1997. Dobson Unit (DU) = 2.69×10^{16} molecules cm^{-2}.

to occur first at upper levels in the stratosphere (30 to 50 km), and so had anticipated that the initial signal of depletion in a total column of ozone would be weak. NASA researchers hastily reviewed their TOMS data and found that it too had detected a dramatic loss of ozone over all of Antarctica. Why hadn't they discovered the phenomenon earlier? Unfortunately, the TOMS data analysis software had been programmed to flag and set aside data points that deviated greatly from expected measurements, and so the initial measurements that should have set off alarms were simply overlooked. In short, the TOMS team failed to detect the ozone depletion years earlier because it was much more severe than expected.

0363-P0085 In the years following the discovery of the ozone hole, NASA and ESA satellites recorded depleting ozone levels over Antarctica growing worse with each passing year. In response, in 1987, 43 nations signed the Montreal Protocol, in which they agreed to reduce the use of CFCs by 50% by the year 2000. This protocol was amended in 1990 to eliminate all CFC emissions by 2000.

0363-P0090 ESA's second European Remote-Sensing Satellite (ERS-2) carries a new sensor called the Global Ozone Monitoring Experiment (GOME). GOME is a nadir-looking sensor with four bands ranging from 240 to 790 nm for measuring backscattered visible and ultraviolet solar radiation. Since the summer of 1996, ESA has routinely produced 3-day global measurements of total ozone and nitrogen dioxide using GOME data.

As recently as 1998, both TOMS and GOME data 0363-P0095 showed that at its Austral spring low, Antarctic ozone concentrations had worsened to 80% less than early 1970s levels. Today there is some evidence that the amount of chlorine in the stratosphere is leveling off. Is this a scientific success story in the making? Will stratospheric ozone concentrations return to pre-1970s levels as the abundance of stratospheric chlorine stabilizes? Only time and continued monitoring will tell. ESA launched its Environmental Satellite (Envisat) in November 2001 with a new sensor called Global Ozone Monitoring by Occultation of Stars (GOMOS).

Chemistry of Earth's Atmosphere

Some satellite sensors allow scientists to determine the 0363-P0100 chemical content of the Earth's upper atmosphere using a technique called solar occultation, in which a sensor is pointed toward the horizon at sunrise and sunset to measure the profile of the stratosphere and mesosphere about 30 times per day. In this way sensors, such as the Stratospheric Aerosol and Gas Experiment (SAGE), can determine the presence and abundance of gases and particulates by measuring

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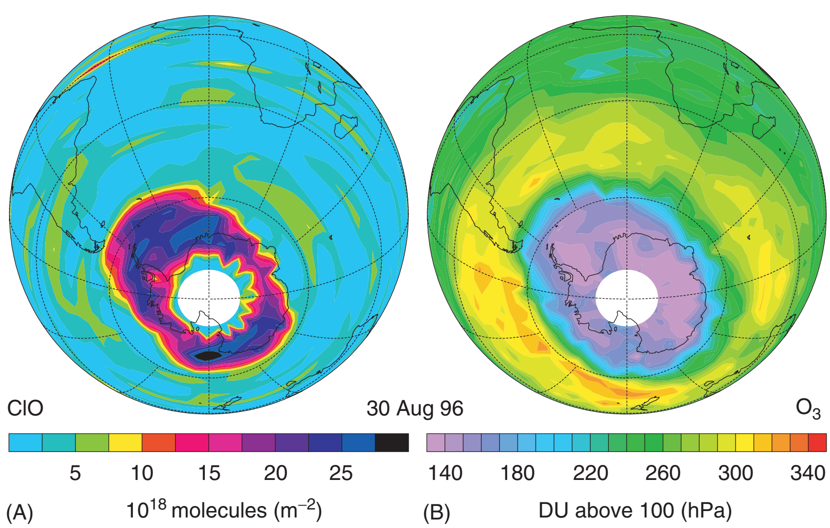
precisely the visible and ultraviolet wavelengths that are absorbed within the upper atmosphere. Since the spectra of ozone, nitrogen dioxide, sulfur dioxide, and certain aerosols are well known, scientists can directly correlate SAGE's readings with the presence of these substances within the stratosphere. The solar occultation technique is particularly effective because the sensor is self-calibrating – each occultation event looks directly at the unattenuated Sun outside the Earth's atmosphere just prior to sunset or just following sunrise. These observations are then compared with observations of the Sun obtained by looking through the atmosphere. The direct Sun observations establish an ongoing baseline of the sensor's performance. Adapted from the Stratospheric Aerosol Mission (SAM II) that flew aboard Nimbus 7, the SAGE sensor is essentially a modified Sun photometer. This kind of sensor first flew in 1979 aboard NASA's Applications Explorer Mission-2 (AEM-2). A subsequent version of SAGE (SAGE II) was launched aboard ERBS in 1984 and performed well throughout 2001, thus giving a 17-year continuous dataset of upper atmosphere profile measurements.

0363-P0105 In 1991, NASA launched the Upper Atmosphere Research Satellite (UARS) with a payload of 10 sensors for measuring a wide array of chemical and physical phenomena in the stratosphere and mesosphere (the layer of atmosphere from approximately 10 to 90 km in altitude). Not only did UARS extend our ability to monitor stratospheric ozone concentrations into the 1990s, but it also provided the first comprehensive picture of the photochemical processes involved in ozone destruction. The UARS Microwave Limb Sounder (MLS) demonstrated that there is a direct link between the presence of chlorine, the formation of chlorine monoxide during winter in the Southern Hemisphere, and the destruction of ozone (**Figure 5**).

UARS carries the first two spaceborne remote wind 0363-P0110
sounders ever launched, called the High Resolution Doppler Imager (HRDI) and the Wind Imaging Interferometer (WINDII). These sensors measure winds in the mesosphere through detection of shifts in airglow emission lines. Additionally, HRDI can detect daytime stratospheric winds by observing Doppler shifts in oxygen absorption lines. WINDII and HRDI gave scientists the first complete global picture of mesospheric circulation. Together with the Halogen Occultation Experiment (HALOE) and MLS aboard UARS, the sensors have enabled researchers to track the upward transport of water vapor in the tropical stratosphere. Most atmospheric water vapor originates from the tropical oceans, where it rises high into the atmosphere to form towering thunderheads. Encircling the globe along the equator is an almost continuous band of thunderheads known as the Intertropical Convergence Zone (ITCZ), producing roughly three-quarters of the energy in our atmosphere that helps to drive its circulation patterns. Data from the sensors just mentioned showed that the tropical tropopause (the gateway from the troposphere to the stratosphere) air rises into the stratosphere through these thunderheads. Once in the stratosphere, this air moves slowly upward and outward toward the midlatitudes. Ozone begins to form as incoming ultraviolet radiation breaks oxygen



0363-F0005 **Figure 5** Chlorine monoxide (A) and ozone concentration (B) derived by MLS at approximately 18 km altitude on 30 August 1996. The high chlorine monoxide within the Antarctic polar vortex in the left-hand figure (reds and dark purple shades) is directly associated with, and leads to, a reduced ozone concentration shown in the right-hand figure (light blue and light purple shades).

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molecules (O_2) into free oxygen atoms (O) that quickly bond with other oxygen molecules to form ozone (O_3). Because ozone strongly absorbs certain wavelengths of ultraviolet radiation, the air begins to warm, helping to perpetuate the upward movement of the air mass as well as helping to create temperature gradients for stratospheric winds. UARS data showed that it takes about 2 years for water vapor anomalies to move from the tropopause (at about 17 km) up to the mid-stratosphere (at about 30 km).

0363-P0115 A Canadian instrument launched in 1999 aboard NASA's Terra satellite uses gas correlation spectroscopy to determine the abundance of methane and carbon monoxide in the troposphere. The Measurements Of Pollution In The Troposphere (MOPITT) sensor measures emitted and reflected radiance from the Earth in three spectral bands. As this light enters the sensor, it passes along two different paths through onboard containers of carbon monoxide and methane. The different paths absorb different amounts of energy, leading to small differences in the resulting signals that correlate directly with the presence of these gases in the atmosphere. Both methane and carbon monoxide are byproducts of burning vegetation as well as fossil fuels. Over the last two decades levels of methane in the atmosphere have risen at an average rate of about 1% per year. This is cause for concern because methane (CH_4) is a greenhouse gas about 30 times more efficient than carbon dioxide at trapping heat near the surface. Scientific interest in carbon monoxide (CO) is twofold. First, the gas controls atmospheric concentrations of oxidants, thus affecting the ability of the atmosphere to clean itself from the ongoing generation of harmful tropospheric ozone from biomass burning and urban smog. Second, through chemical reactions within the lower atmosphere, carbon monoxide contributes to the production of harmful ozone. MOPITT is helping researchers to identify the main sources of these gases as well as to improve four-dimensional models of their transport through the atmosphere.

0363-P0120 ESA's Envisat will carry the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), which is an advanced version of the GOME sensor flying aboard ERS-2. In addition to the same four spectral channels contained on GOME (from visible to ultraviolet wavelengths; 240–800 nm), SCIAMACHY has an additional four channels in the infrared region of the spectrum (800–2400 nm). While the sensor's wide spectral sensitivity makes it useful for cloud and aerosol research, its ability to view both nadir and the Earth's horizon makes it useful for determining the content and distribution of 16 different trace gases in the atmosphere.

Where Storm Clouds Gather

0363-P0125 Rain clouds form when moisture-laden air is driven skyward by warm updrafts emitted from a Sun-warmed land or ocean surface; or when mountain slopes push moist air aloft; or when a wedge of colder, denser air plows warmer, moist air upward to higher elevations. Because cold air cannot hold as much water vapor as warm air, and because the atmosphere cools at higher elevations, water vapor condenses readily into liquid droplet or ice crystal form, in the presence of seed aerosol particles. Were there no aerosol particles in the Earth's atmosphere, there would be no fog, no clouds, no mist, and probably no rain. When water evaporates at the surface, it absorbs energy from its surroundings and stores it as latent heat. When water vapor condenses back into liquid or ice form it releases its latent heat into its surroundings. Only about 25% of the energy contained within the atmosphere comes directly from the Sun's rays; the remaining 75% comes from the release of latent heat contained in water vapor, most of which, as mentioned, is present in the towering thunderheads of the Intertropical Convergence Zone (**Figure 6**).

0363-P0130 We cannot measure the latent heat contained within clouds. We can, however, measure tropical rainfall. Currently, there is a 50% uncertainty in estimates of annual global rainfall. If we are to determine more accurately how much energy our atmosphere receives from latent heat, then we must more accurately measure rainfall. In 1997, NASDA and NASA jointly developed and launched the Tropical Rainfall Measuring Mission (TRMM) into a midinclination (35°) precessing orbit. It is estimated that about 60% of precipitation on Earth falls within the band between 30° N and 30° S of the Equator. TRMM carries three instruments designed to measure rainfall – the Precipitation Radar (PR), the TRMM Microwave Imager (TMI), and the Visible and Infrared Scanner (VIRS). Designed and built by NASDA, the Precipitation Radar is the first satellite sensor to provide three-dimensional images of the internal structures of storm clouds. Its measurements show the intensity and distribution of rain within a storm, the total height of a storm, and the elevation at which ice crystals melt into raindrops. Most importantly, the Precipitation Radar can measure rain rates to within 0.7 mm per hour. Researchers who expected to use ground-based Doppler Radar stations to validate TRMM's Precipitation Radar measurements found much to their pleasant surprise that the latter exceeds most ground-based measurements in accuracy and spatial resolution.

0363-P0135 The TMI is a "passive" sensor designed to measure minute amounts of microwave energy emitted by the

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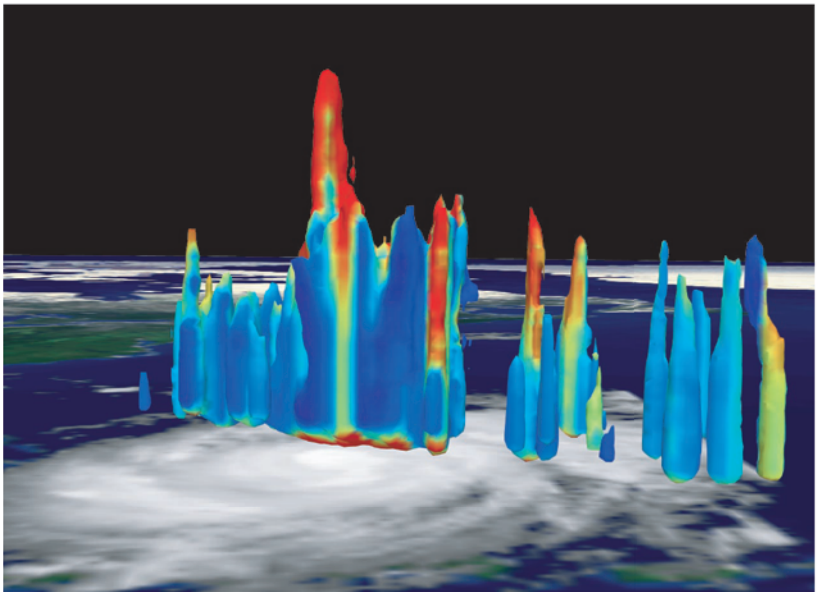

0363-F0006 **Figure 6** Hurricane Bonnie as observed by the TRMM/PR on 22 August 1998. Red shows intense precipitation, green and yellow hues are intermediate values, and blues are low values. The eye of the storm reached to 16 km.

Earth's surface and from within its atmosphere. (Whereas "active" sensors send pulses of energy and then measure how much gets absorbed and reflected by the target, "passive" sensors measure only energy originating from, or reflected by external sources.) These measurements allow TMI to quantify the amount of water vapor, cloud water, and rainfall intensity within the atmosphere. Based upon the design heritage of the Defense Meteorological Satellite Program's Special Sensor Microwave/Imager (SSM/I), the TMI has a wider viewing swath (780 km) and finer spectral resolution than its predecessors. The TRMM VIRS detects radiant energy in five spectral bands, ranging from visible to infrared wavelengths (from 0.63 to 12 μm). Ideally designed to measure temperature, VIRS can precisely determine cloud top temperatures that scientists can then indirectly correlate with rainfall amounts.

Conclusion

0363-P0140 As the preceding sections demonstrate, the Earth's atmosphere changes both physically and chemically over a range of scales of time and space. The atmosphere's chemical makeup affects its physical state, such as its radiative properties. As already mentioned, the gases and particles in the atmosphere function much like a venetian blind, selectively absorbing and reflecting certain wavelengths of solar radiation while allowing others to pass through relatively unhindered. In turn, physical processes in the atmosphere also help determine its chemical makeup. There was growing consensus through the 1970s and 1980s among Earth scientists that we needed to take a more holistic approach to global climate change studies. We saw that nature does not compartmentalize climate phenomena into discrete disciplines, and therefore we need to examine the variables of change as integral parts of the vast, interconnected web of cause and effect that is Earth's climate system. In short, it is not enough to identify where and when changes occur; we need to understand how and why the mechanisms of change work. Satellite remote sensors offer the only viable means of conducting a comprehensive examination of our planet.

See also

(349) (349). **(361)** (361). **Aerosols:** Observations and Measurements (48). **Radiative Transfer:** Absorption and Thermal Emission (337); Scattering (340). **Satellite Remote Sensing:** Cloud Properties (348); Precipitation (352); TOMS Ozone (351). **Satellites:** Orbits (362).

Further Reading

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