The Earth's Changing
as Seen From

EARTH

by Michael D. King

Earth's land, oceans, and atmosphere are being watched from space. Earth-orbiting satellites, representing a technology only 50 years old, have transformed our understanding of the planet's natural variability and enabled us to see how our planet is being modified by human activity. This is a perspective on Earth that previous generations could only dream about.

The era of remote sensing began in the late 1960s and early 1970s, when instruments on Earth-oriented spacecraft first observed our planet from above. Without regard to political boundaries and human-created structures, these observations opened the public's eyes to our precious planet, as well as to its vulnerability and susceptibility to natural and anthropogenic development.

Consider, for example, that land and ocean surfaces, like the semipermanent ice caps and seasonally varying polar sea ice, often change dynamically, with sometimes strikingly large short-term changes on top of seasonal and interannual variations. Glaciers and other forms of land ice generally change slowly, creeping up or down their tracks, but sometimes they collapse unexpectedly.

Can we notice such phenomena while standing on the ice? Of course we can. From the vantage point of space, however, using the extraordinary technological developments of the last decade, we can observe changes in Earth's environment that are simply not visible, or at least not practically observable, from ground-based, shipborne, or airborne instruments. The Earth-observing satellites of today have evolved in capability from the earliest Earth-orbiting satellites, and they are monitoring and helping us understand the many changes that are rippling through our planet's climate system.

In this article, I will explain some of the ways we watch from space as our planet changes below our "eyes in the sky."

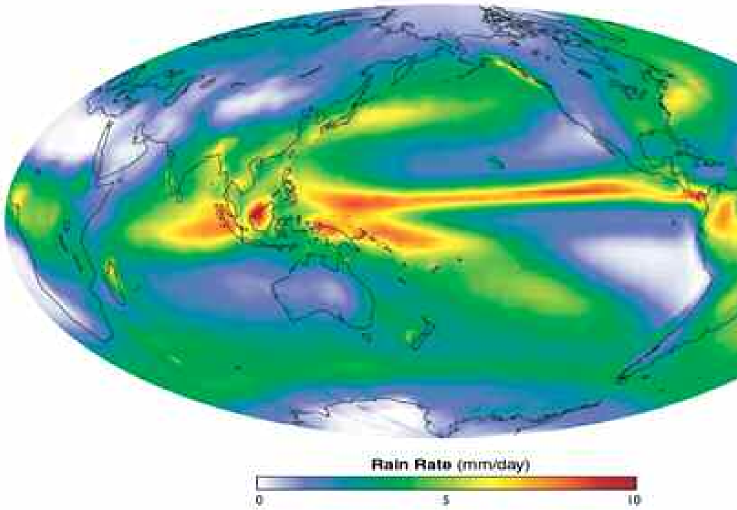


Figure 1 ***Humans have always been concerned about rainfall. The distribution of forest, desert, and arable land is determined to a large extent by the relative abundance or absence of precipitation. This image shows the average precipitation across Earth's surface between 1979 and 2006. The highest global precipitation (shown in red) is in the tropics.*** *Image: Data from the Global Precipitation Climatology Project*

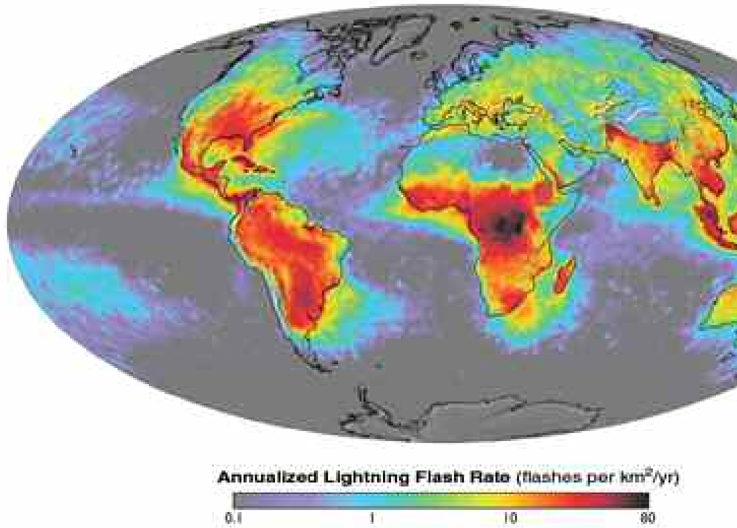


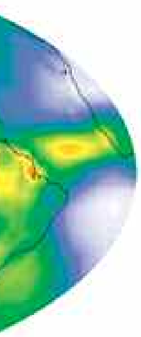
Figure 2 ***Because lightning storms often are seen prior to severe storms, monitoring the lightning flash rate of thunderstorms aids forecasters in predicting and detecting severe weather. This image shows the mean annual global lightning flash rate, derived from a combined eight years, from April 1995 to February 2003.*** *Image: Data from the OTD instrument on the* OrbView-1 *satellite and the LIS instrument on the* TRMM *satellite*

Precipitation—Rain and Snow

To sustain life on Earth, rain must fall and snow must melt to provide the liquid to drive the water cycle. Spaceborne microwave radiometers have been measuring this precipitation for nearly 30 years. Based on these observations, we now know that the average depth of global precipitation—averaged over an entire year and assuming that it didn't sink into the soil or run off to the sea—would create a liquid layer of about one meter, or about waist deep. The amount of rain varies tremendously across Earth's surface, however, as shown in **Figure 1**; most falls in the tropical western

Environment

Space



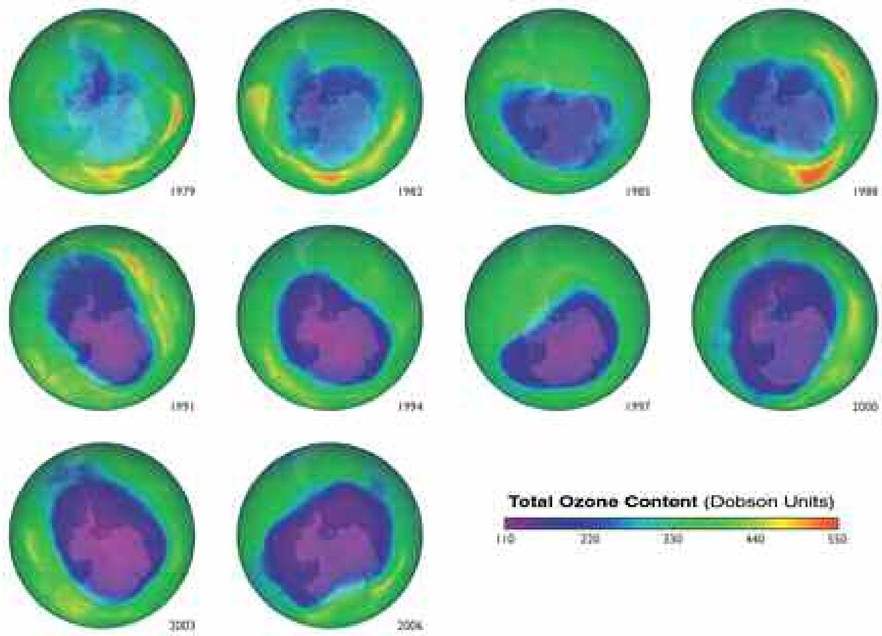
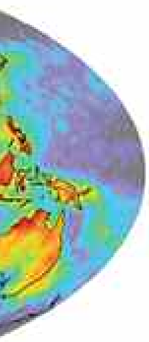


Figure 3 ***The stratospheric ozone layer protects Earth's surface from the Sun's harmful ultraviolet radiation. The minimum ozone content in the Southern Hemisphere occurs over Antarctica during September and October. This sequence shows the minimum total ozone for selected years from 1979 to 2006.***

Image: Data from the TOMS instrument on the Nimbus 7, Meteor 3, *and* Earth Probe *satellites, as well as the OMI instrument on* Aura.



Pacific and the tropical jungles of the Amazon basin of South America and the Congo basin of Africa. Meanwhile, across vast desert regions, there is scant precipitation.

Precipitation varies spatially, and there is also considerable variability over the years, which is associated with irregular tropical patterns such as El Niño, La Niña, and the monsoon circulation on the Indian subcontinent. Space-based technologies allow us to track these phenomena worldwide without relying on local rain gauges, and all nations of the world use satellite data to monitor drought, extreme rainfall, floods, and climate variations.

Lightning Strikes

Another natural phenomenon that injures and kills people worldwide is lightning, which was first monitored from space in 1995. Space-based observations have confirmed that about 90 percent of all lightning occurs over land. Oceanic lightning appears primarily along warm ocean currents with deep convective activity, such as the Gulf Stream of the North Atlantic and the Agulhas Current of South Africa.

Figure 2 shows the annual average lightning flash rate, based on satellite observations between 1995 and 2003. These data reveal that the Congo basin of central Africa is the lightning "hot spot" of the world, with a rate of 158 flashes per square kilometer per year, and that lightning is more prevalent in the summer months, owing to deep convective cloud activity. Overall, there is very little lightning north of the east-west band of mountains that extends from Europe across Asia. These mountains serve to limit the poleward flow of tropical moisture.

The Ozone Hole

Ground-based observations first alerted us to the increase in carbon dioxide concentration since the Industrial Revolution and the decrease in stratospheric ozone over Antarctica in the austral spring, producing the so-called ozone hole. Satellite and aircraft data have increased our understanding and subsequently played a key role in establishing the size and transformation of the ozone hole over the Antarctic.

Since 1978, satellites have monitored the ozone hole's areal extent, depth, and dynamic evolution (see **Figure 3**). They are crucial in monitoring ozone recovery and the yearly variability expected following the Montreal Protocol, which restricted the emission of ozone-depleting substances. Upper-atmospheric ozone is expected to recover to its 1980 level by about 2070. During the annual peak in ozone hole size, in late September and early October, the ozone hole has attained a size of more than 25 million square kilometers

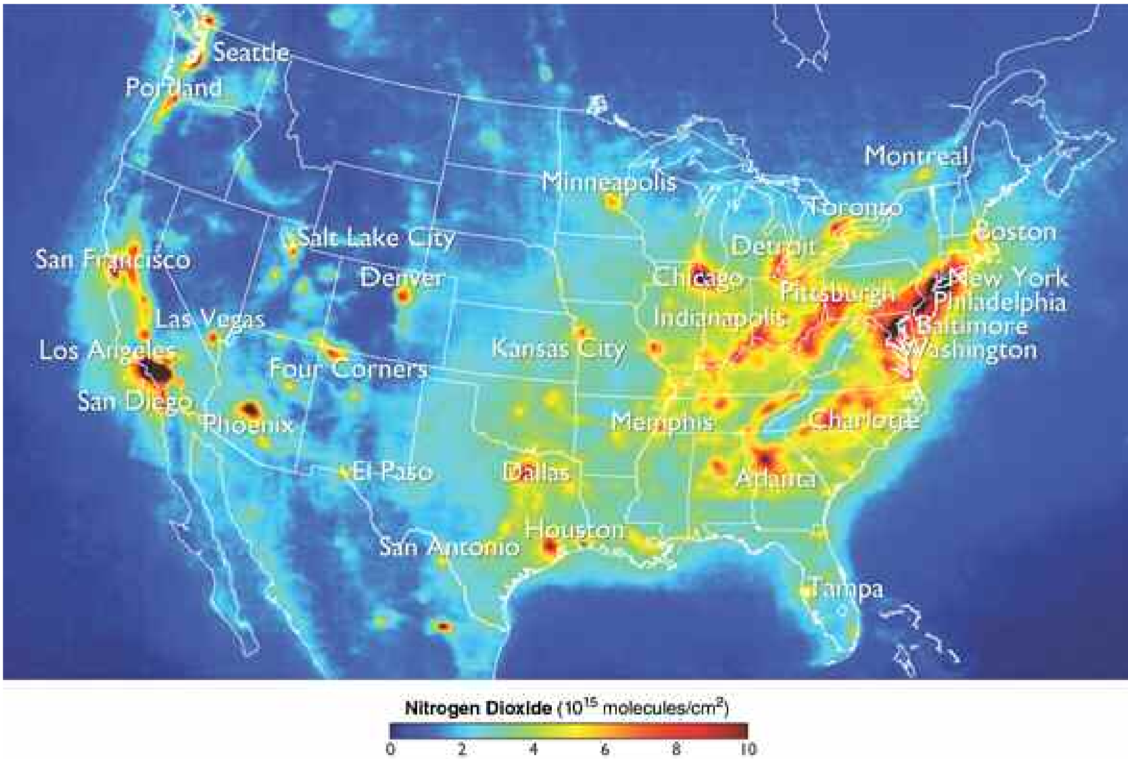


Figure 4 ***The principal sources for nitrogen dioxide (NO_2) in Earth's troposphere occur over large populated regions, heavily industrialized areas, and individual power plants. This image shows the annually averaged NO_2 for the continental United States for 2006, clearly revealing the high concentration of NO_2 above numerous cities throughout the country.***

Image: Data from the OMI instrument on the Aura satellite

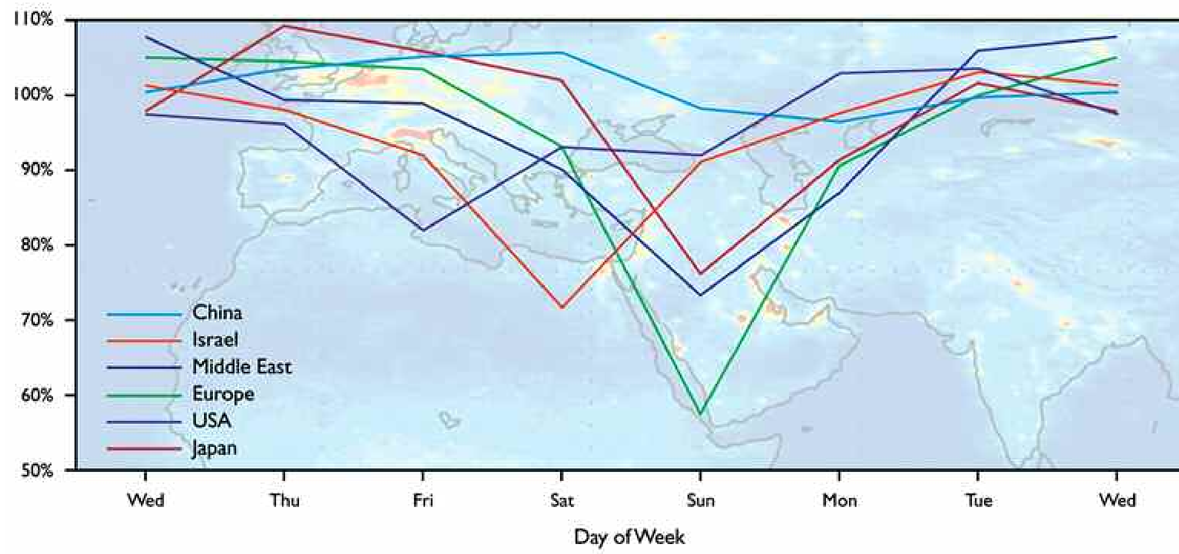


Figure 5 ***Human transportation practices in Western countries follow the seven-day cycle, and consequently many emissions are reduced over weekends. This figure illustrates the "weekend effect" for selected regions as observed from space. All plots are normalized with respect to the median value for Monday–Thursday.***

Image: Data from the GOME instrument on the ERS-2 satellite

in some recent years, exceeding the area of the entire North American continent.

Constituents of Earth's Atmosphere

Satellites can monitor our atmosphere's constituents, including water vapor, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). NO_2 is a short-lived, human-made chemical of the lower atmosphere that leaves a daily signal reflecting human activity. All major cities of the world, as well as industrial coal-fired power plants, are evident from space-based observations of NO_2.

Figure 4 shows the annually averaged tropospheric NO_2 for the continental United States for 2006, clearly revealing the high concentration of NO_2 along the Interstate 95 corridor of the northeastern United States, as well as above numerous cities throughout the country. There is also a high concentration of NO_2 along the Ohio River Valley and the Four Corners region of the Southwest, associated with coal-fired power plants.

When plotted globally, the daily satellite data reveal that the eastern United States and Europe (especially the Po Valley of Italy) see a large reduction in NO_2 concentration on Sunday, reflecting the day of rest in predominantly Christian nations. In contrast, the Islamic countries of the Middle East exhibit their lowest NO_2 concentration on Friday, while in Israel, the lowest NO_2 concentration occurs on Saturday, the Jewish Sabbath. This day-of-the-week signal, clearly evident in **Figure 5**, follows as a consequence of the short lifetime of NO_2 in the atmosphere and the religious preferences of people in different regions, which are reflected in the use of transportation conveyances.

Rising Sea Level

The rise in sea level is an unfortunate and unintended consequence of burning fossil fuels and clearing forests, activities that warm the lower atmosphere system by increasing atmospheric carbon dioxide. The sea level responds because ocean waters expand as they warm and because of the melting of land ice caps, including the Greenland and Antarctic ice sheets.

Sea level, which rose in the late 20th century by approximately 3.1 millimeters (0.1 inch) per year, is not uniform around the globe. Space-based radar altimeters, orbiting Earth continuously since 1992, have allowed us to monitor the spatial and temporal patterns. This would not be possible using only tide gauges located along continental shorelines and a few islands in the open ocean.

Figure 6 shows the spatial distribution of sea level change from 1993 to 2006. It reveals that the rise is greatest in the sensitive tropical western Pacific, with its high concentration of low-lying island nations. The change in sea level arises primarily from thermal expansion as the ocean's surface warms and cools.

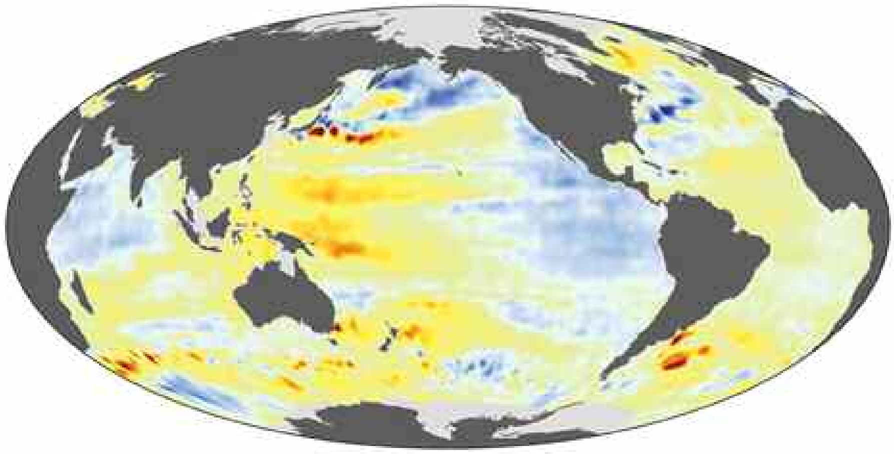


FIGURE 6 ***Current estimates indicate that more than one third of the world's population lives within 100 kilometers (about 60 miles) of coastline. This map shows the spatial distribution of sea level change (measured in millimeters per year) from 1993 to 2006. It reveals that the rise is greatest in the tropical western Pacific.*** *Image: Data from the* TOPEX/Poseidon *and* Jason-1 *altimeter missions*

Earth's Surface Temperature

Satellites today enable us to measure temperatures on the sea surface as well as on land. The land measurements complement the air temperature measurements that are routinely taken two meters above ground at meteorological stations throughout the world. By comparing the satellite-derived land surface data for a given period or time of day with the average over many years, we can infer large-scale heat waves or abnormally cold episodes.

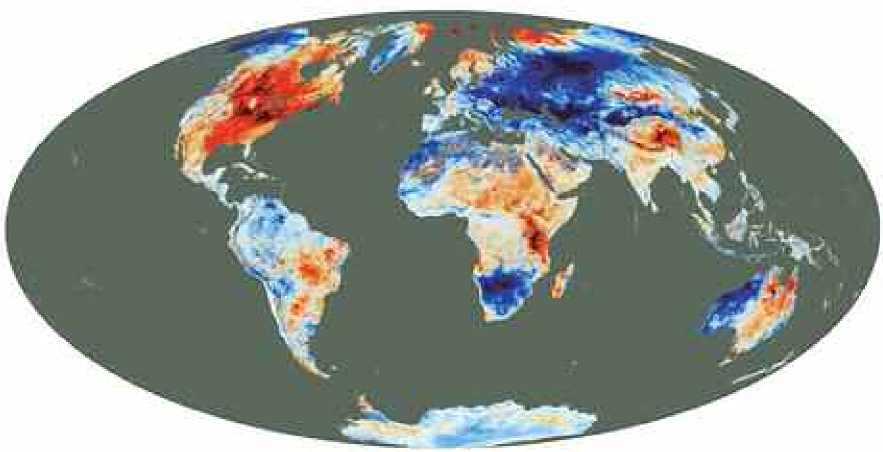


FIGURE 7 ***In January 2006, the eastern half of the United States experienced unusually mild temperatures while vast areas of Europe, Asia, southern Africa, and western Australia experienced temperatures that were 10 degrees Celsius (18 degrees Fahrenheit) colder than normal. This map illustrates the temperature anomaly for January 1–24, 2006, in contrast with the average for that period from 2001 to 2005.*** *Image: Data from the MODIS instrument on the* Terra *satellite*

Figure 7 illustrates the temperature "anomaly" for January 1–24, 2006 in contrast with the average for that period from 2001 to 2005. In January 2006, the U.S. news media focused on the unusually warm winter in the eastern United States and the abnormally cold winter in Moscow. **Figure 7** greatly broadens the discussion, showing the global picture and indicating that the land was more than 10 degrees Celsius (18 degrees Fahrenheit) colder than normal throughout eastern Europe and much of the Russian Federation, as well as in southern Africa, western Australia, and Alaska. The abnormal warmth experienced in the eastern United States extended well into Canada and also was exhibited in east Africa, Tibet, and northern Australia. Observa-

tions such as these rely on thermal emissions from the land surface and can be obtained for multiple times of day. They are widely used to forecast crop productivity and to assess drought.

Fire

Taking advantage of the intense thermal emission from hot fires, satellites also are used to monitor fires worldwide. **Figure 8** illustrates the annual distribution of fires for 2005, based on satellite analysis from the Moderate Resolution Imaging Spectroradiometer on the *Terra* and *Aqua* Earth Observing System missions.

On a global basis, most fires occur in Africa, primarily as the result of clearing land for agriculture, a practice dating from at least 100,000 years ago. Archaeological evidence suggests that fire might have been exploited in eastern Africa as early as 1.6 million years ago. Although widespread, especially in the tropics, fires are largely set during the "dry season." The widespread fires seen in **Figure 8** in sub-Sahelian Africa occur primarily in December, January, and February, whereas the fires in southern Africa (Angola, Zambia, Mozambique, and Malawi) occur primarily in August, September, and October.

Globally, fires in North America are few but intense, and they often are suppressed when they approach residential areas or population centers. Although some of these fires are set by humans, most are started by lightning. Again, satellites provide a uniform and border-independent way of assessing the transformation of the landscape.

Changing Land Use

Satellites often have been used to assess the transformation of open land to urban use as cities develop and rural areas are transformed by roads,

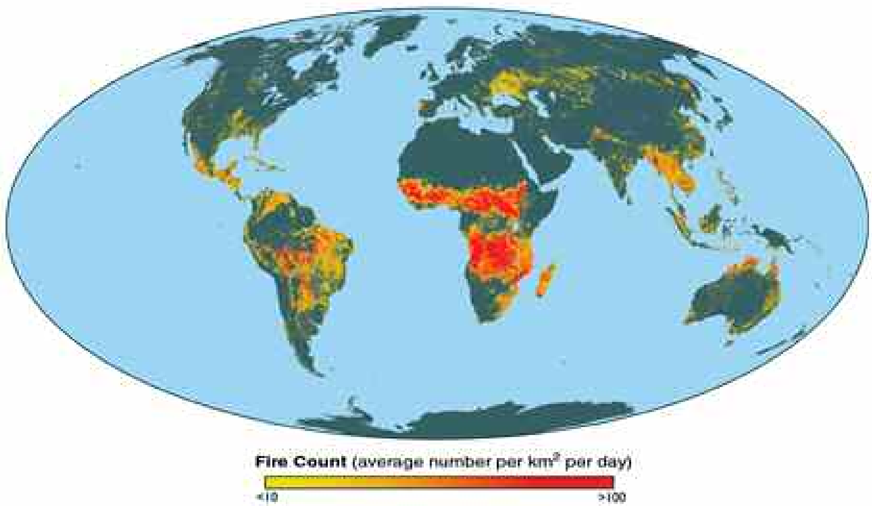


Figure 8 ***The frequency, intensity, seasonal timing, and type of fire that prevail in a region are referred to as the*** **fire regime.** ***Scientists are eager to understand whether the world's fire regimes are changing. Pictured here is the annual global distribution of fires in 2005. The widespread fires seen in sub-Sahelian Africa occur primarily in December, January, and February, whereas the fires in southern Africa (Angola, Zambia, Mozambique, and Malawi) occur primarily in August, September, and October.*** *Image: MODIS Rapid Response Team; data from the MODIS instruments on the* Terra *and* Aqua *satellites*

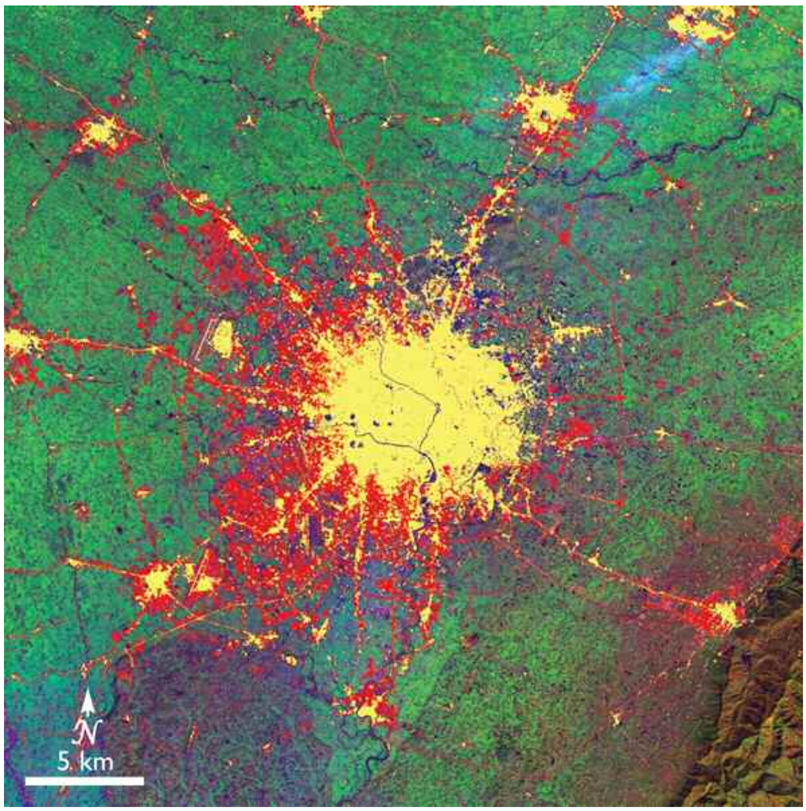


Figure 9 ***This image shows how Chengdu, a city in China, changed over a decade. The base satellite image was taken in November 2000, with vegetation represented in green, water in dark blue/black, and bare ground in purple. Maps of urban extent have been added to the image, with yellow depicting the amount of urban land cover circa 1990 and orange showing the amount of land developed between 1990 and 2000.*** *Image: Data from the ETM+ instrument, bands 7, 4, and 2, on the* Landsat 7 *satellite*

Here, There, and Not Quite Everywhere

Some of the earthly phenomena that satellites monitor from space also occur on other worlds. Here's a brief look at those mentioned in this article.

Precipitation—It's just a light drizzle, but it falls all the time on Titan, Saturn's largest moon. The temperature there is about –150 degrees Celsius (about –240 degrees Fahrenheit), so the rain that falls is liquid methane. At depths within the gas giant planets, deeper than we can see, other strange species of rain also may be falling.

Lightning—Thunderstorms big enough to swallow Earth rage around Jupiter, generating lightning 10 times as powerful as any strike on our planet. From radio signals detected by passing spacecraft, we know that lightning occurs on Venus, Saturn, Uranus, and Neptune as well.

Ozone (O_3)—Nasty-smelling ozone occurs on other worlds, but not in quantities large enough to form an atmospheric layer that can block ultraviolet (UV) light from the Sun—and protect organic things from that damaging radiation. Mars has traces of ozone in its atmosphere, but not enough to shield its surface from UV rays. The top layers of soil are effectively sterilized.

Nitrogen dioxide (NO_2)—This noxious creation of human industry is not found on other worlds. Earth alone must cope with it.

Sea level—On Earth, mean sea level is the reference point for measuring height and depth on the surface. On Jupiter's moon Europa, the entire world beneath the ice is covered by an ocean. Determining sea level there is a problem future explorers would like to solve.

Surface temperature—Our benign climate is perfect for life as we know it, but Earth is a neighborhood anomaly. Temperatures on other worlds range from about 480 degrees Celsius (almost 900 degrees Fahrenheit) on the surface of Venus to around –230 degrees Celsius (–380 degrees Fahrenheit) on Pluto. Even a minor change in average temperature can tip the balance, positively or negatively, for terrestrial life-forms.

Planetary surface—Some worlds in our solar system may have no solid surface at all. On these gas giants, the gases just get denser and denser with depth until, for example at Jupiter, the lightest element in the universe—hydrogen—is compressed into liquid metal.

Fire—Should we ever detect fire on another world, we will have found a signature of life. To start the chemical reaction we call fire, an oxidizer is necessary. On Earth, we would run out of the oxygen we breathe unless plants continually replenished it. Without plant life, oxygen would react with minerals and metals to get locked away in rocks.

Land use—As far as we know, Earth is the only planet with life-forms that modify its atmosphere and surface. For most of humanity's history, these changes were invisible from space. Now our "eyes in the sky" look down on cultivated fields, diverted rivers, and city lights at night, all dramatic demonstrations of our species' power over the planet.

—Charlene M. Anderson, Associate Director of The Planetary Society

buildings, and housing. **Figure 9** shows how Chengdu, a city in China, changed between 1990 (yellow) and 2002 (orange). Population growth forces changes in land use, which are easiest to monitor and map worldwide using high-resolution satellites from the *Landsat* series that date from 1972.

Earth-orbiting satellites enable us to observe our changing environment in ways that are impossible to accomplish from the ground. The land, atmosphere, ocean, and cryosphere are readily observable from space, often at less expense and effort than using land-based methods. This short article cannot address all the phenomena we monitor from space. Other phenomena not illustrated in this article include

- stratospheric sulfur dioxide (SO_2) arising from volcanic eruptions
- tropospheric SO_2 arising from coal-fired power plants and copper smelters
- the spatial distribution of human-made and natural aerosol particles
- the vertical distribution of many atmospheric constituents
- sources and sinks of carbon in the oceans and on land
- wind speed and direction over the global oceans
- sea ice extent and change
- glacier extent and ice sheet topography
- surface reflectance and the length of the growing season
- cloud cover and microphysical properties of liquid water and ice clouds.

Satellite imagery and data analysis can show more readily than any other means the large-scale state of the Earth-atmosphere-ocean system, its many dynamic processes, and the evolution of conditions worldwide. Our planet is changing, and only from space can we monitor it effectively.

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Images adapted from the book Our Changing Planet: The View From Space *by Michael D. King, Claire C. Parkinson, Kim C. Partington, and Robin G. Williams, Cambridge University Press, 2007.*