NASA's Earth Observing System: The Transition from Climate Monitoring to Climate Change Prediction

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Introduction

Earth's 4.5 billion year history is a study in change. Natural geological forces have been rearranging the surface features and climatic conditions of our planet since its beginning. There is scientific evidence that some of these natural changes have not only led to mass extinctions of species (e.g., dinosaurs), but have also severely impacted human civilizations. For instance, there is evidence that a relatively sudden climate change caused a 300-year drought that contributed to the downfall of Akkadia, one of the most powerful empires in the Middle-East region around 2200 BC. More recently, the "little ice age" from 1200-1400 AD forced the Vikings to abandon Greenland when temperatures there dropped by about 1.5°C, rendering it too difficult to grow enough crops to sustain the population. Today, there is compelling scientific evidence that human activities have attained the magnitude of a geological force and are speeding up the rate of global change. For example, carbon dioxide levels have risen 30 percent since the industrial revolution and about 40 percent of the world's land surface has been transformed by humans.

We don't understand the cause-and-effect relationships among Earth's land, ocean, and atmosphere well enough to predict what, if any, impacts these rapid changes will have on future climate conditions. We need to make many measurements all over the world, over a long period of time, in order to assemble the information needed to construct accurate computer models that will enable us to forecast climate change. In 1988, the Earth System Sciences Committee, sponsored by NASA, issued a report calling for an integrated, long-term strategy for measuring the vital signs of Earth's climate system. The report urged that the measurements must all be intimately coupled with focused process studies, they must facilitate development of Earth system models, and they must be stored in an information system that ensures open access to consistent, long-term data. This committee emphasized that the only feasible way to collect these consistent, long-term data is through the use of space-based Earth "remote sensors" (instruments that can measure from a distance things like temperature). Consequently, in 1990, NASA initiated the Earth Observing System (EOS) as part of the Presidential initiative, Mission to Planet Earth, which received its 'new start' approval from Congress in October. When initiated, this ambitious global change program was projected to cost $17 billion from inception through October 2001. EOS' projected budget was repeatedly cut in subsequent years to focus primarily on global *climate* change, to increase use of multiple smaller spacecraft, and re-

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duce the cost of sensors and platforms through, in part, reliance on international partners, The EOS program is funded today at $6.2 billion through October 2001.

The EOS mission is comprised of three integral parts: 1) a series of satellites that are specially designed to study change on local, regional, and global scales; 2) an EOS Data and Information System (EOSDIS), which is an advanced computer network designed to receive, process, store, and distribute the terabytes (10^{12} bytes) of data that the EOS satellites transmit home each week; and 3) teams of Earth scientists all over the world, and from all Earth science disciplines, who will study the data and interpret their meaning.

In 1994, the EOS scientific community identified 24 critical variables (see Table 1) that form the foundation for a coordinated research program to study the Earth's climate system. With EOS, for the first time ever for a major satellite mission, the goals include freely sharing the resulting data with both scientists and civilian stakeholders alike. This treatment of data contrasts sharply with previous satellite missions for which public access to data was quite costly. In fact, some EOS data will be directly broadcast to anyone anywhere who has a compatible receiving station and the capacity to process and store such a huge flow of information. As its name suggests, EOS is a large, long-term collaborative mission involving scientists in government agencies, academia, and industry from many nations.

Science Goals and Objectives

The EOS mission continues investigations begun more than 100 years ago by two pioneering physicists: Samuel Langley and Svante Arrhenius. In the 1880s, Langley invented the Bolometer radiometer, an instrument that enabled him, for the first time ever, to accurately measure transmissions of sunlight and heat through the Earth's atmosphere, and to distinguish those wavelengths that are transmitted from those absorbed. So, for example, pointing his Bolometer at the moon allowed Langley to measure—or "remotely sense"—its temperature. Based upon Langley's work, in 1896 Arrhenius developed the first global climate model that enabled him to predict Earth's average surface temperature as a function of atmospheric carbon dioxide levels. He calculated (without computers!) that if, through the consumption of fossil fuels, humans double the amount of carbon dioxide in the atmosphere, then the average global temperature would rise by 5.7°C. One hundred years later, we find that global carbon dioxide has risen by about 30 percent and that average global temperature has risen by 0.5°C; whereas it was expected to rise by about 1.0°C. This tells us that other physical and chemical forces are at work in the Earth's climate system that Arrhenius' model (and even our best computer models today) do not take into account. There exists today much scientific uncertainty (not to mention political tension) surrounding issues like global warming. If we are to improve our predictive models—indeed, if humans are to be the best stewards of the Earth that we can be—then we must improve our understanding of its climate system.

In 1999, EOS will begin its comprehensive study of the Earth with the launches of Landsat 7 and QuikSCAT (in the spring), and Terra and Meteor-3M (in the fall). (Terra, EOS' flagship satellite, was formerly called "EOS AM-1.") Together, these satellites will pioneer calibrated, multi-spectral observations from space. The goal is to begin what will become, at a minimum, a 15-year global data set from which we can study the causes and effects of climate change. In subsequent years, NASA will launch EOS PM-1 and ICESat to both extend and add to the EOS data sets. The EOS objectives are to understand Earth's climate system well enough to predict changes, and to differentiate those changes that are natural from those that are human-induced.

A Multidisciplinary Approach

In 1965, in his *New Intelligent Man's Guide to Science*, Isaac Asimov wrote:

> "With each generation of scientists, specialization has grown more and more intense. The publications of scientists concerning their individual work have never been so copious—and so unreadable for anyone but their fellow specialists. This has been a great handicap to science itself, for basic advances in scientific knowledge often spring from cross-fertilization of knowledge from different specialties."

For the EOS mission to succeed, cross-fertilization of knowledge across multiple science disciplines is both a requisite, and an anticipated byproduct. The project directly supports about 800 Earth scientists working in government agencies and academia around the world. Their investigations span four broad spheres of study—including the life sciences (biosphere); water, snow and ice (hydrosphere); volcanoes and land surface dynamics (lithosphere); and winds, clouds, aerosols, and radiation (atmosphere). Within each of these spheres of knowledge today there are key pieces of information missing—pieces we must find if we are to resolve the complex jigsaw puzzle of climate change.

It is impossible to assemble the jigsaw puzzle all at once. Each piece of information from every discipline must be carefully considered with respect to the big picture before we know how it fits. Already there are some key pieces in place and an interesting picture of Earth's climate system is beginning to emerge. In this light, perhaps the best way to understand the anticipated contributions from EOS is to consider the mission within the context of the portions of the climate change picture that we already see clearly.

The Chemistry of Ozone Depletion

In the early 1970s, atmospheric chemists began to suspect that human-released chlorine compounds could destroy ozone (specifically, the "good" ozone in the Earth's stratosphere that absorbs much of the sun's harmful ultraviolet rays). Scientists predicted that if the early 70s rate of chlorofluorocarbon (CFC) emissions continued, about 5 percent of stratospheric ozone would be destroyed by the year 2050. Based upon this information, the U.S. government banned the use of CFCs in aerosol spray products in 1978. In

1979, NASA launched its Total Ozone Mapping Spectrometer (TOMS) aboard the Nimbus-7 satellite to begin measuring concentrations of stratospheric ozone on a global scale. But, ironically, scientists missed the fact that TOMS was reporting severe ozone depletion over Antarctica. This is because their computer processing procedures were set to dismiss as "unreliable" ozone levels below 180 Dobson units—the very low ozone levels that would have alarming consequences on human populations. (A Dobson unit equals 10^{-5} meters of ozone in a vertical column of atmosphere at standard temperature and pressure.)

In 1985, we were alerted to our oversight when a British Antarctic Survey team made a series of ground-based Dobson ozone spectrophotometer measurements of total ozone from Halley Bay, Antarctica. The team made international headlines when they reported finding a more than 40 percent reduction in stratospheric ozone there. Scientists at NASA quickly reprocessed the TOMS data and verified the British Antarctic Survey team's findings. Consequently, in 1987 some 150 scientists representing 19 different organizations from four different countries met in Chile to conduct a large-scale scientific study of the Antarctic stratosphere. Instruments aboard NASA's ER-2 aircraft (a modified U-2), flew into the Antarctic polar vortex where they recorded for the first time ever a direct correlation between elevated levels of chlorine monoxide and reduced levels of ozone. In response to this conclusive proof that humans were destroying Earth's vital ozone "shield," in 1987, the Montreal Protocol was adopted to reduce CFC emissions to half of 1986 levels by the year 2000. This Protocol was amended in 1990 to eliminate all CFC emissions by 2000. As recently as 1998, TOMS data show that at its autumn low, Antarctic ozone concentrations had worsened to 80 percent less than early 1970s levels.

In 1991, NASA launched a Microwave Limb Sounder (MLS) aboard its Upper Atmosphere Research Satellite (UARS) to measure, for the first time ever, chlorine monoxide on a global scale. In 1993, the MLS investigators confirmed that chlorine chemistry is the primary cause of Antarctic ozone depletion. Even more significantly, MLS showed that stratospheric chlorine over the poles can be "activated," or converted by natural forces from dormant chemical forms to active ones, like chlorine monoxide. The MLS showed us that the stratosphere over the North Pole also contains higher than normal levels of chlorine monoxide during late winter and early spring, destroying ozone there at rates of up to 0.7 percent per day, although the problem is much less severe in the Arctic than in the Antarctic. [Figure 1]

Did the Montreal Protocol solve the ozone depletion problem? Will stratospheric ozone concentrations return to pre-1970s levels as the abundance of stratospheric chlorine stabilizes? Or, are there other potentially negative impacts on ozone that are related to greenhouse gas emissions and climate change that we haven't anticipated? Some scientists have suggested that El Niño could have an impact on ozone concentrations. To help us answer these important questions, and to extend the MLS data set, EOS Chemistry-1 will launch in 2002 with a payload of state-of-the-art sensors for monitoring atmospheric chemistry on an ongoing basis. The EOS Chemistry satellite will improve our ability to monitor ozone, in part, because it will fly closer to the poles (98° inclination, whereas UARS flew at 57° inclination). Its measurements will be more frequent, more accurate, and will provide better spatial resolution—extending down into the upper troposphere. Most importantly, the new MLS will provide an unprecedented ability to measure stratospheric hydroxyl. Hydroxyl is a radical that is integral to all stratospheric chemistry; so, to better understand the stratosphere and ozone loss mechanisms, we must understand hydroxyl. EOS Chemistry-1 will also have instruments for measuring tropospheric chemistry, total ozone content, aerosol properties, and concentrations of many other stratospheric chemistry species.

Is Earth's Energy Budget Balanced?

Measuring the amount of incoming solar radiation at the top of Earth's atmosphere over the course of a year, and then averaging that amount, yields a number that is referred to as the "energy budget." Then, measuring the amount of radiation escaping from the top of the Earth's atmosphere (reflected sunlight and emitted heat), and subtracting that number tells us whether the energy budget is in balance. If the amount of incoming solar energy exceeds the amount of outgoing energy, then there is a budget surplus and the Earth is warming. If the numbers are the same, then the Earth is in steady state; and if the outgoing energy exceeds that which is incoming, then there is a budget deficit and the Earth is cooling.

Until the mid-1980s, we didn't know the status of the Earth's energy budget, but a number of scientists were already predicting global warming. Then, in 1984, NASA launched it's the first of three Earth Radiation Budget Experiment (ERBE) payloads to measure radiative flux in the Earth's atmosphere. During its 5-year life-time, ERBE scanner measurements showed a net annual imbalance in the energy budget—slightly more energy was being absorbed by the Earth each year than was emitted. But whether this imbalance was real, or merely an "artifact" of the satellite is still a matter of scientific uncertainty. [Figure 2]

Moreover, and more importantly, ERBE showed that, in the current climate, cloud cover exerts a cooling effect on the Earth-atmosphere-ocean system. This finding settled a long-standing debate as to whether clouds exert a net cooling influence on the surface by reflecting and absorbing sunlight, or a net warming influence by trapping and containing heat emitted from the surface. Unfortunately, ERBE was not designed to clearly discern certain key parameters in the atmosphere (i.e., reflectance and/or absorption by clouds), nor those on the surface (reflective ice sheets versus reflective clouds in the Arctic), that significantly affect the Earth's radiation budget. In short, ERBE cannot tell us what happens to solar radiation once it enters the atmosphere. Hence, it cannot tell us why there was an energy imbalance or where the energy is absorbed.

Comparing satellite data with ground-based and aircraft-based measurements, we find that we cannot account for about 8 percent (or 25 Watts per square meter) of incoming solar radiation once it enters the Earth's atmosphere. Is this missing energy being primarily absorbed and scattered by clouds and aerosols (tiny solid or liquid particles suspended in the atmosphere)? Is this energy somehow being sequestered in the deep ocean? Or, perhaps the answer is some combination of all these possibilities. We need better data to answer these questions—data that Terra will collect every day over our entire planet. Terra will carry a pair of sensors, called Clouds and the Earth's Radiant Energy System (CERES), that will extend and improve upon the ERBE scanner data set. Specifically, CERES will measure radiative flux, twice as accurately as ERBE, at both the top of the atmosphere and at the surface. With the aid of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra, which will provide information on cloud radiative and microphysical properties, including thermodynamic phase of cloud particles, CERES will be better able to quantify the roles clouds play in the Earth's energy system.

Mystery in a Cloud, Wrapped in Haze

We cannot predict where and when clouds and aerosol concentrations will occur, but it will help us immensely to know where and when they do. Perhaps clouds and aerosols are part of the reason that the Earth's average temperature has risen by only half of what our models predict. These atmospheric constituents represent the areas of greatest scientific uncertainty regarding influences on climate. Therefore, an important first step toward unraveling the mystery of the missing solar radiation is to be able to measure the changing reflective and absorptive properties of clouds and aerosols on an ongoing basis. Here, the CERES sensors will be greatly complemented by two other sensors aboard Terra—the Moderate-resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging Spectroradiometer (MISR).

MODIS and MISR each have unique design features that are ideal for measuring clouds and aerosols. Whereas CERES has relatively low resolution (a single CERES pixel is 20 kilometers at nadir), MODIS and MISR will measure cloud and aerosol properties at moderate resolutions (ranging from 250 meters to 1.1 kilometer at nadir). MODIS, with its specially designed spectral bands in the visible and infrared regions of the spectrum, as well as its wide spatial coverage, will measure daily the percent of the Earth's surface that is covered by clouds. It will also have an unprecedented ability to observe thin cirrus clouds; to both quantify their impact on the energy budget and to "correct" for their presence in remote sensing scenes used to examine surface or lower-level features. MODIS will enable us to monitor how aerosols are transported by wind currents, as well as how they mingle with clouds and alter their optical properties. In complementary fashion, MISR will measure the angular reflective properties of clouds and aerosols at nine different look angles, thereby enabling us to construct 3-dimensional computer models of their structures and microphysical properties. MISR will be particularly useful for tracing aerosols and smoke plumes back to their original sources. [Figure 3 and Figure 4]

Greenhouse Gases: A Hot Topic

Water vapor is by far the most significant greenhouse gas for trapping and containing heat emitted from the Earth's surface and from within its atmosphere. Water vapor is the most variable trace gas in the atmosphere, with numerous spectral bands that absorb solar radiation and Earth-emitted thermal radiation; therefore, it presents the largest uncertainty regarding its impact on climate. The greater the temperature at the Earth's surface, particularly at the ocean's surface, the more water evaporates into the atmosphere. Therefore, in a warming climate system, there is a positive feedback loop that can amplify climate change. Computer models suggest that this water vapor feedback loop enhances the greenhouse effect by about 1 percent, or 1.3 Watts per meter squared, per degree of warming. In the long run, we don't know whether changes in the hydrological cycle will speed up global warming by increasing water vapor concentrations at high altitudes, or counteract it by forming more low clouds to shade and cool the surface.

On average, water vapor concentration depends on temperature, which governs the total amount of waver that the atmosphere can hold without saturating. Globally, precipitation balances with evaporation, so greater surface temperatures result in more evaporation, and hence greater precipitation. Recent studies confirm this relationship. Data collected from 1900-1988 show that global rainfall amounts increased at a rate of 2.4 mm per decade. In other words, about 22 mm more rainfall will fall on our planet this year than in 1900. For the first time ever, MODIS will measure globally both surface temperature and the distribution of water vapor in the lower atmosphere, thereby enabling scientists to directly observe and correlate the dynamic positive feedback loop involving these two parameters. We expect these data to help us improve models for predicting when and where severe precipitation, or drought, events will occur.

Methane is another atmospheric gas that significantly contributes to Earth's greenhouse effect—greater on a per molecule basis than carbon dioxide, for example. Sources of this gas include northern wetlands, livestock herds, and natural gas leakages. However, the output of these individual sources is not known. We do know that, globally, methane is rising in the atmosphere at a rate of about 1 percent per year. Terra will carry an instrument called Measurements of Pollution in the Troposphere (MOPITT, built by a consortium of Canadian companies) that will measure concentrations of methane and carbon monoxide in Earth's lower atmosphere, both as a function of latitude and longitude and, in the case of CO, of altitude. MOPITT's measurements will help us better understand how the lower atmosphere reacts to various stimuli, ranging from natural phenomena such as the growth of forests, to agricultural sources such as rice paddies, to catastrophic events like biomass burning. Ultimately, MOPITT will provide new insights into the processes by which chemical reactions occur in the lower atmosphere. It will contribute to improved 4-dimensional models of the transport mechanisms by which large concentrations of these gases may be traced back to their sources.

Carbon dioxide, considered the key greenhouse gas, gets most of the scientific scrutiny these days. Like water vapor, it is naturally abundant in the Earth's atmosphere, and it traps and contains a significant amount of heat near the surface. Yet, carbon dioxide is also a byproduct of human industry, which has driven up levels in the atmosphere by about 30 percent over the last 100 years. Today, it is rising at a rate of 0.5 percent per year. Our colleagues (V. Ramanathan and James Hansen) estimate that carbon dioxide alone accounts for 50 to 65 percent of the human contribution to global warming. Unlike water vapor, it takes 100 to 200 years for the atmosphere to establish a new balance if a large amount of carbon dioxide is suddenly added.

We cannot precisely account for where all this carbon is going. Of the almost 7 billion tons of carbon released into the atmosphere each year, about half remains in the atmosphere. Most of the rest gets absorbed into the ocean (about 3 billion tons per year) or by terrestrial plants (anywhere from 0.5 to 1 billion tons per year), primarily through photosynthesis. Yet, we do not know what happens to 1 to 3 billion tons of the world's annual carbon budget. Are we underestimating the terrestrial and/or oceanic carbon sinks? Or, perhaps we are underestimating the amount that remains in the atmosphere? If so, then average temperatures should be warmer and there are other variables that are somewhat offsetting this expected warming. While no EOS satellite is designed to directly observe atmospheric carbon dioxide concentrations around the world, Terra and Landsat 7 will observe and help us quantify those terrestrial and oceanic dynamics that play critical roles in the global carbon cycle.

Changing our Landscapes: For Better or Worse?

Global change seems most "obvious" when we consider its patterns on Earth's landscapes. Human population has tripled over the last century, resulting in expanding urban centers that can be easily seen from space at night as dense clusters of light. To meet our needs for space, energy and food, humans have altered about 40 percent of the world's land surface cover. In this same time period, biomass burning—the most widely used method for clearing away forests for agriculture, cattle grazing, and urban development—has quadrupled. [Figure 5] Burning away the forest has a two-fold effect on the carbon cycle: (1) it releases stored carbon into the atmosphere, and (2) it eliminates vegetation that would otherwise be absorbing carbon from the atmosphere during photosynthesis. The Terra and Landsat 7 satellites will enable us to differentiate between those land surface changes that are natural and those that are human-induced, as well as to better quantify how surface changes alter a given region's capacity to reflect or absorb solar radiation (thereby affecting Earth's energy budget). Moreover, EOS' high resolution sensors will enable us to monitor the rate at which deserts, forests, lakes, and glaciers may be expanding or diminishing.

Using MODIS, MISR, and Landsat 7 data we will be able to construct improved global vegetation maps to provide up-to-date estimates of the areal distribution of Earth's major terrestrial vegetation types. MODIS and MISR will "see" the surface at moderate resolution, while the Enhanced Thematic Mapper Plus (ETM+) aboard Landsat 7 will "see" at resolutions of up to 15 meters. Landsat 7 will continue and expand upon the data set begun by the first Landsat mission launched in 1972. Additionally, Terra will carry the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, developed by Japan's Ministry of International Trade and Development). ASTER is comprised of three subsystems that have the ability to tilt their viewing angles to view specific targets of interest (such as erupting volcanoes, large fires, etc.) at high resolution (up to 15 m). Because the ASTER visible subsystem has two telescopes, one looking backward (along track) and the other looking towards nadir, it will provide stereoscopic measurements that will enable us to dramatically improve our digital topographical models of the Earth's surface. In addition, MODIS will permit us to monitor the frequency, temperature, and areal extent of fires worldwide. [Figure 6]

The sensors aboard Terra and Landsat 7 will enable us to gauge the annual productivity of forests and, therefore, quantify their roles in the global carbon cycle. Computer models suggest that if there is an increase in carbon dioxide levels, and if there is a corresponding increase in average temperatures, then there should also be an observable increase in land vegetation productivity. EOS scientists (Myneni *et al.*) verified this relationship recently in a paper published in *Nature*. They found that due to a rise in average temperatures at high northern latitudes, the growing season is expanding while the rate of plant productivity is increasing. Additionally, coupling observations of land surface change and deforestation patterns with measurements of precipitation and atmospheric water vapor concentrations will help us assess the impacts of deforestation on regional hydrological cycles.

Earth's Heat Engine

Covering more than 70 percent of our planet and holding 97 percent of its surface water, the ocean has been called the "Earth's heat engine" due to its influence on the timing and patterns of climate change. The Earth's ocean and atmosphere are locked in such an intricate embrace that as one changes so changes the other. At the interface between air and sea there is a constant flow of information as vast amounts of energy (in the form of heat and momentum) and chemicals (in the form of gases and aerosols) are continually being exchanged. As heat rises and eventually escapes the ocean to warm the atmosphere, it creates air temperature gradients and, consequently, winds. In turn, winds push against the sea surface and drive ocean current patterns.

In 1996, NASA launched the NASA Scatterometer (NSCAT), a microwave scatterometer, aboard the Japanese ADEOS (Advanced Earth Observing Satellite) spacecraft. During the brief lifetime of that mission, NSCAT measured with unprecedented accuracy, resolution, and global coverage the speed and direction of winds over the ocean. Unfortunately, the ADEOS solar panel failed after only 10 months of operation, rendering its payload—including NSCAT—inoperable. This spring's launch of the QuikSCAT satellite is NASA's quick response to fill the gap in the surface wind data left by the

ADEOS failure. QuikSCAT will carry a new version of NSCAT, called SeaWinds, that will see 90 percent of the Earth's entire surface every day, enabling oceanographers to correlate and better quantify the physical relationship between the ocean and atmosphere. SeaWinds data will be particularly useful in early detection of when Pacific trade winds shift, signaling the onset of El Niño. [Figure 7]

The ocean stores far greater reserves of heat and carbon than the land or atmosphere. Over geological time, more than 90 percent of the Earth's carbon has settled into the deep ocean. Should it become a net source rather than a sink of heat and carbon, the impacts on global climate would be catastrophic—exceeding by far the effects of El Niño. But, on the contrary, there is evidence that in recent decades the ocean has exerted a cooling effect on global temperature, which could explain why greenhouse gas warming hasn't been more severe. Despite the frequent and increasingly intense El Niños, data suggest that average sea surface temperatures in the eastern Pacific have fallen in recent decades. It is possible that this temperature trend, coupled with the formation of more low clouds, has helped offset global warming somewhat. It is also possible that, through greater biological productivity, the ocean is becoming a more efficient carbon dioxide sink, thereby again helping to offset global warming. To understand the myriad roles of the ocean in climate change, we need better data.

Reliable sea surface temperature measurements from space-based sensors have been a goal of oceanographers since the late 1960s. Following on the success of the NOAA Advanced Very High Resolution Radiometer (AVHRR) and European Space Agency's Along Track Scanning Radiometer (ATSR), the MODIS sensor on Terra and EOS PM-1 will continue measurements of the global sea surface temperatures with projected accuracies to within 0.5 K. These data, coupled with SeaWinds data, will help us improve our models of the ocean's circulatory patterns as well as ocean-atmosphere coupling, particularly during El Niño and La Niña events.

Terra and EOS PM-1 will also help us quantify the ocean's role in the carbon cycle. MODIS will make global scale measurements of phytoplankton (microscopic marine plants), as well as dissolved organic matter in the upper ocean. By precisely measuring ocean color, we can accurately estimate the concentrations of phytoplankton on a global scale. Globally, and over geological time, phytoplankton is the driving force (dubbed the "biological pump") behind sequestration of carbon into the deep ocean—more than 90 percent of the world's carbon has settled there. MODIS will provide an unprecedented capability to measure fluorescence—an indicator of the rate at which phytoplankton are photosynthesizing—which will help us gauge the efficiency with which the biological pump is transferring atmospheric carbon to the ocean.

A New Generation of Remote Sensors

Before launch, EOS' new generation of satellite sensors are calibrated to an unprecedented degree to ensure their data are accurate to within strict spectroradiometric standards specified by NASA and the U.S. National Institute of Standards and Technology (NIST). To ensure that the data are accurate throughout the lifetime of each mission, onboard calibration devices are added to each satellite sensor. Moreover, Terra and PM-1 will periodically roll over so that they can view the moon—a well-understood and stable reflector. The scientific community has consistently recommended that NASA deliberately include some overlap of data types across some EOS sensors and missions so that they may be cross compared to ensure that they are all "seeing" the same signals. Finally, EOS satellite data will be compared with data from dozens of ground-based and airborne instruments to ensure that the data are valid throughout the lifetimes of each mission. In short, the EOS mission gives us the best ever tools for conducting a global examination of Earth and diagnosing its "health." It will likely take a year after the launch of Terra for the first four-dimensional "snapshot" of our planet to emerge, and possibly several years after that to complete the first thorough statistical evaluation.

Conclusion

Like an incredibly complex jigsaw puzzle, Earth's climate system is intricately interconnected. Each piece of the puzzle—from its hydrological cycle to its energy budget to its biosphere—interacts to form a unique and beautiful whole.

Although this article has touched upon a wide range of Earth science disciplines to which EOS data will be applied, it has still only scratched the surface. Many of its contributions will undoubtedly be serendipitous as innovative new studies and new applications emerge in the years after launch. Toward this end, EOS data will be freely shared with scientists and commercial "stakeholders" worldwide. For further information and updates on the EOS program and its scientific results, see http://eos.nasa.gov.

Further Reading

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ADDITIONAL IMAGES AND INFORMATION are available from the World Wide Web at http://eos.nasa.gov

Table 1: Key physical variables needed to advance understanding of the entire Earth system and the interactions among the components. The EOS spacecraft listed in bold font are primary missions, bold italics represent secondary missions, and roman fonts are contributing instruments for critical measurements.

Discipline	Measurement	EOS Spacecraft
ATMOSPHERE	Cloud Properties (amount, optical properties, height)	**Terra**, **PM-1**, **ICESat**, Meteor-3M
	Radiative Energy Fluxes (top of atmosphere, surface)	**TRMM**, **Terra**, **ACRIM**, **PM-1**, ***ICESat***, Meteor-3M
	Precipitation	**PM-1**
	Tropospheric Chemistry (ozone, precursor gases)	**Terra**, **Chemistry-1**, TRMM, Meteor-3M
	Stratospheric Chemistry (ozone, ClO, BrO, OH, trace gases)	**Meteor-3M**, **Chemistry-1**
	Aerosol Properties (stratospheric, tropospheric)	**Meteor-3M**, ***Chemistry-1*** **Terra**, ***ICESat***, ***Chemistry-1***
	Atmospheric Temperature	**PM-1**, **Chemistry-1,** Terra
	Atmospheric Humidity	**PM-1**, ***Chemistry-1***, ***Meteor-3M***, Jason-1, Terra
	Lightning (events, area, flash structure)	**TRMM**
SOLAR RADIATION	Total Solar Irradiance	**ACRIM**, **TSIM**
	Ultraviolet Spectral Irradiance	**SAVE**
LAND	Land Cover & Land Use Change	**Landsat 7**, **Terra**
	Vegetation Dynamics	**Terra**, **Landsat 7**
	Surface Temperature	**Terra**, **PM-1**, Landsat 7
	Fire Occurrence (extent, thermal anomalies)	**Terra**, Landsat 7
	Volcanic Effects (frequency, thermal anomalies, impact)	**Terra**, **Landsat 7**
	Surface Wetness	**PM-1**
OCEAN	Surface Temperature	**Terra**, **PM-1**
	Phytoplankton & Dissolved Organic Matter	**Terra**
	Surface Wind Fields	**QuikSCAT, ADEOS II**, PM-1, Jason-1
	Ocean Surface Topography	**Jason-1**
CRYOSPHERE	Land Ice (ice sheet topography, ice sheet volume change, glacier change)	**ICESat**, **Terra**, **Landsat 7**
	Sea Ice (extent, concentration, motion, temperature)	**PM-1**, **Jason-1**, Terra, Landsat 7
	Snow Cover (extent, water equivalent)	**Terra**, **PM-1**, **Landsat 7**

CAPTIONS

Figure 1. These stratospheric ozone data were collected by NASA's Microwave Limb Sounder (MLS) on February 20, 1996. For both the northern and southern hemisphere, the images show a direct correlation between temperature, nitric acid, chlorine monoxide, and ozone depletion. Chlorine monoxide is the dominant form of reactive chlorine that destroys ozone. The double white lines surrounding the polar regions denote the boundary of the polar vortex. The white circular area over the pole is where no measurements were obtained.

Figure 2. These global data, collected by NASA's Earth Radiation Budget Experiment (ERBE), show the total amount of incoming solar radiation absorbed by the Earth in comparison to the amount of heat escaping from the Earth for the years 1985-86. During this period, the net energy balance was positive (more energy was absorbed from the sun than was emitted back into space) in the tropics and negative at high latitudes.

Figure 3. This artist's rendering of the Multi-angle Imaging Spectroradiometer (MISR) shows how it will view the Earth at nine different look angles, each in four different wavelengths (red, green, blue, and near-infrared) of the spectrum. MISR's design features render it an excellent tool for stereoscopically measuring the interactions among aerosols, clouds, and radiation.

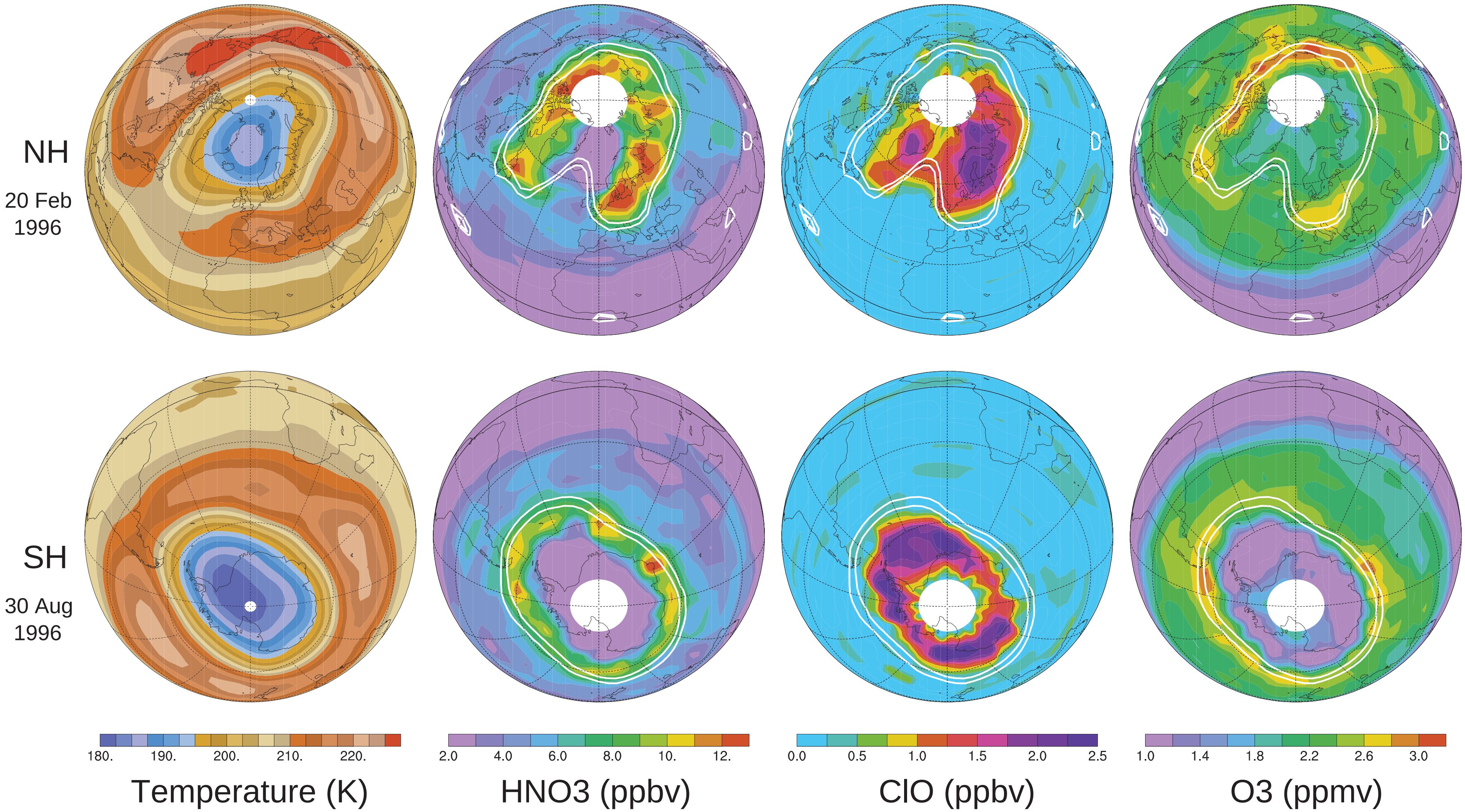
Figure 4. This Earth image is synthesized from four remotely sensed data layers: visible light reflection over land (SeaWiFS), fires over land (AVHRR), aerosols over the ocean (AVHRR), and infrared cloud images from four geostationary satellites. The large aerosol plume over the Atlantic is from biomass burning and windblown desert dust emitted over Africa.

Figure 5. These Advanced Very High Resolution Radiometer (AVHRR) images of Africa—taken in September 1992 and January 1993, respectively—show where vegetation is thriving (green and dark green) due to frequent monsoon rains, and where biomass burning is widespread (red pixels) due to drought and dry surface conditions. Worldwide, deforestation and slash-and-burn agriculture account for most of the biomass burned in the tropics.

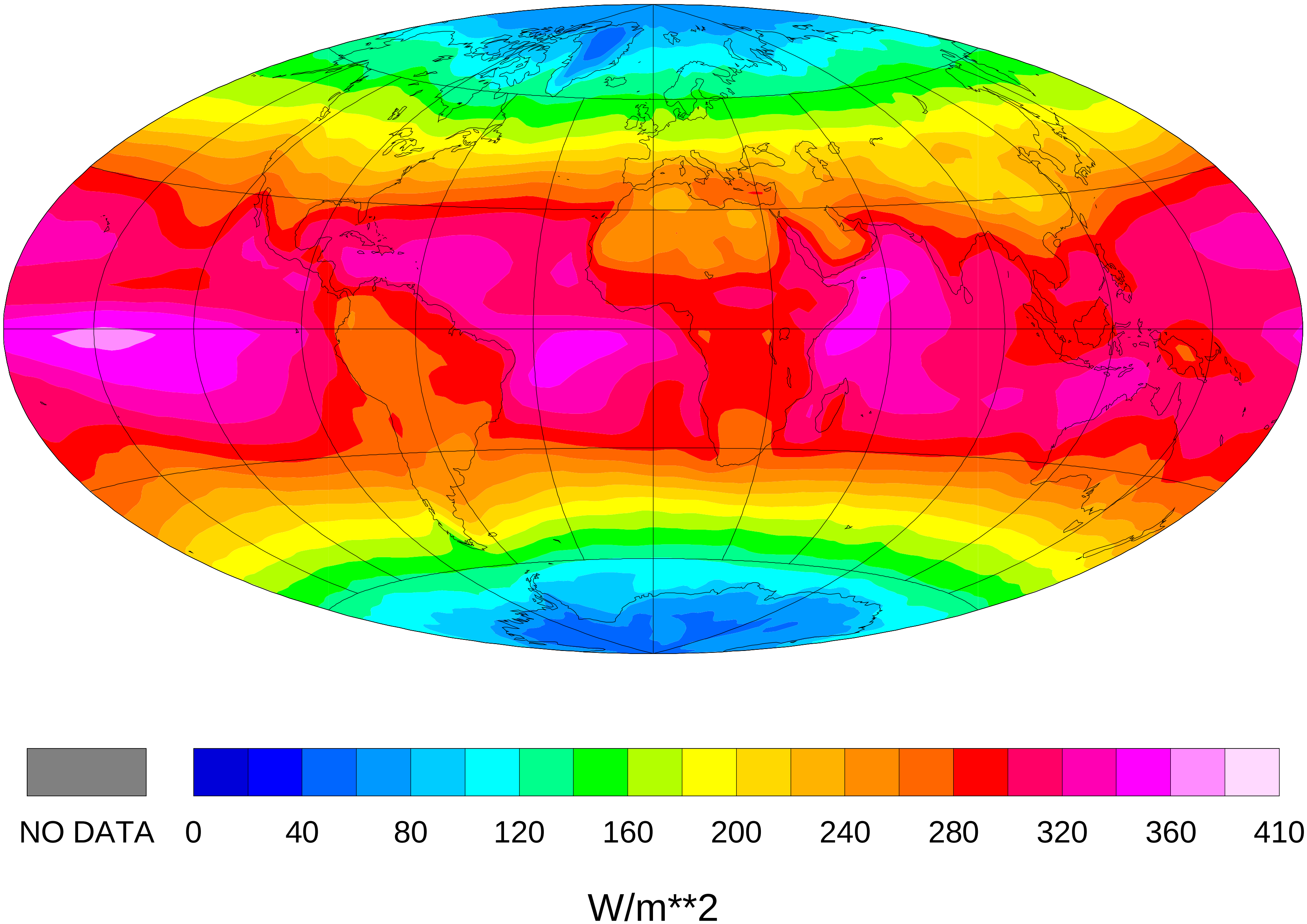
Figure 6. The Terra spacecraft, scheduled to launch in August 1999, will circle the Earth from pole-to-pole and gather multi-spectral images of our entire planet almost daily to help us monitor climatic and environmental change. This image shows the Moderate resolution Imaging Spectroradiometer's (MODIS) 2,300-kilometer-wide viewing swath. Actual data from NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) were used to show how remote sensors can detect concentrations of plant life, both on land and in the ocean.

Figure 7. This image shows ocean surface wind speeds and directions over the Pacific Ocean on September 21, 1996, as they were measured by the NASA Scatterometer (NSCAT) onboard Japan's Advanced Earth Observing Satellite (ADEOS). The background color indicates wind speed and the white arrows show the direction of the wind. Two typhoons (yellow spirals) are shown in the western Pacific.

Earth's Lower Stratosphere in 1996 Northern and Southern Winters

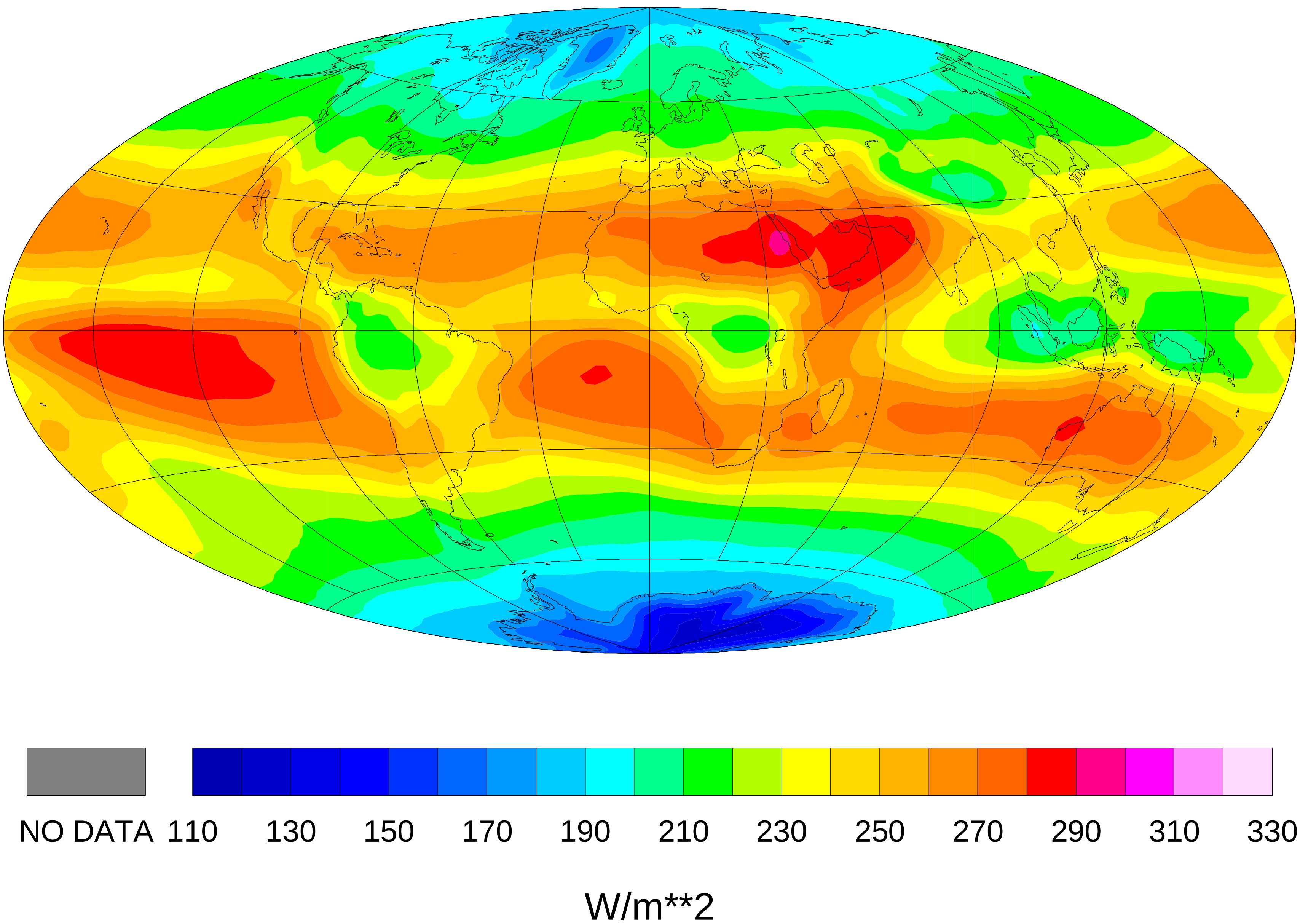


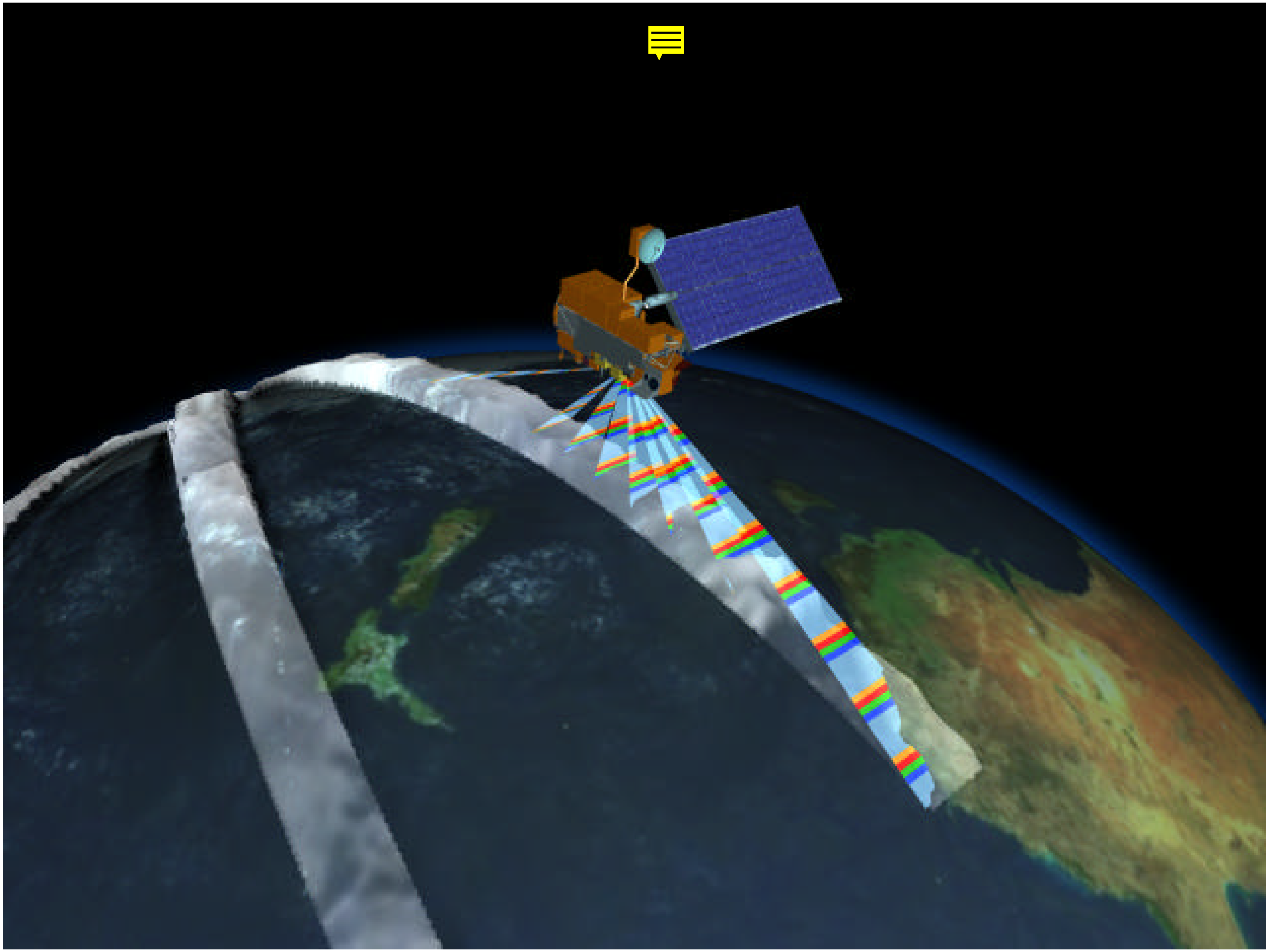
Absorbed Shortwave Radiation
1985-1986

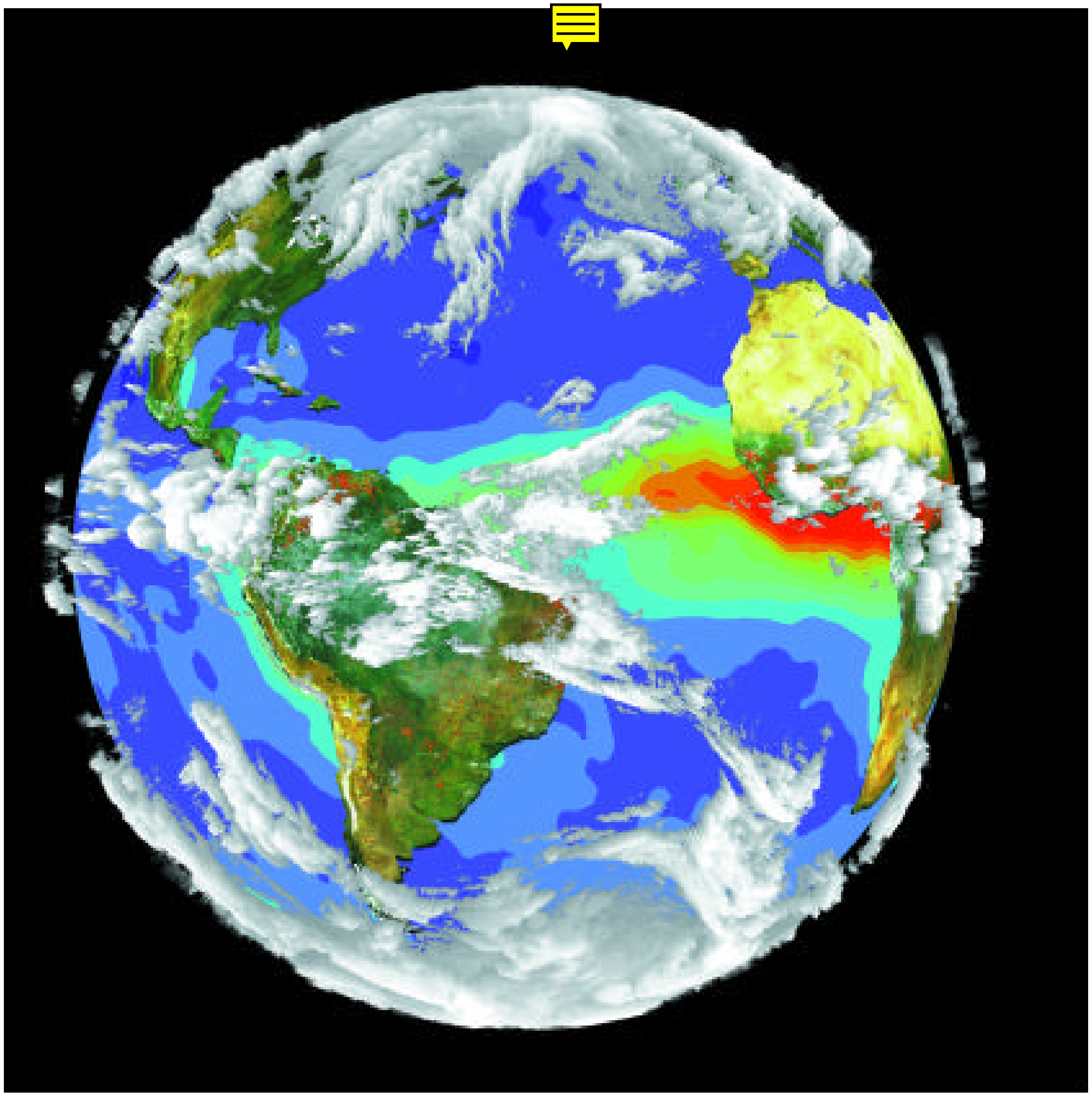


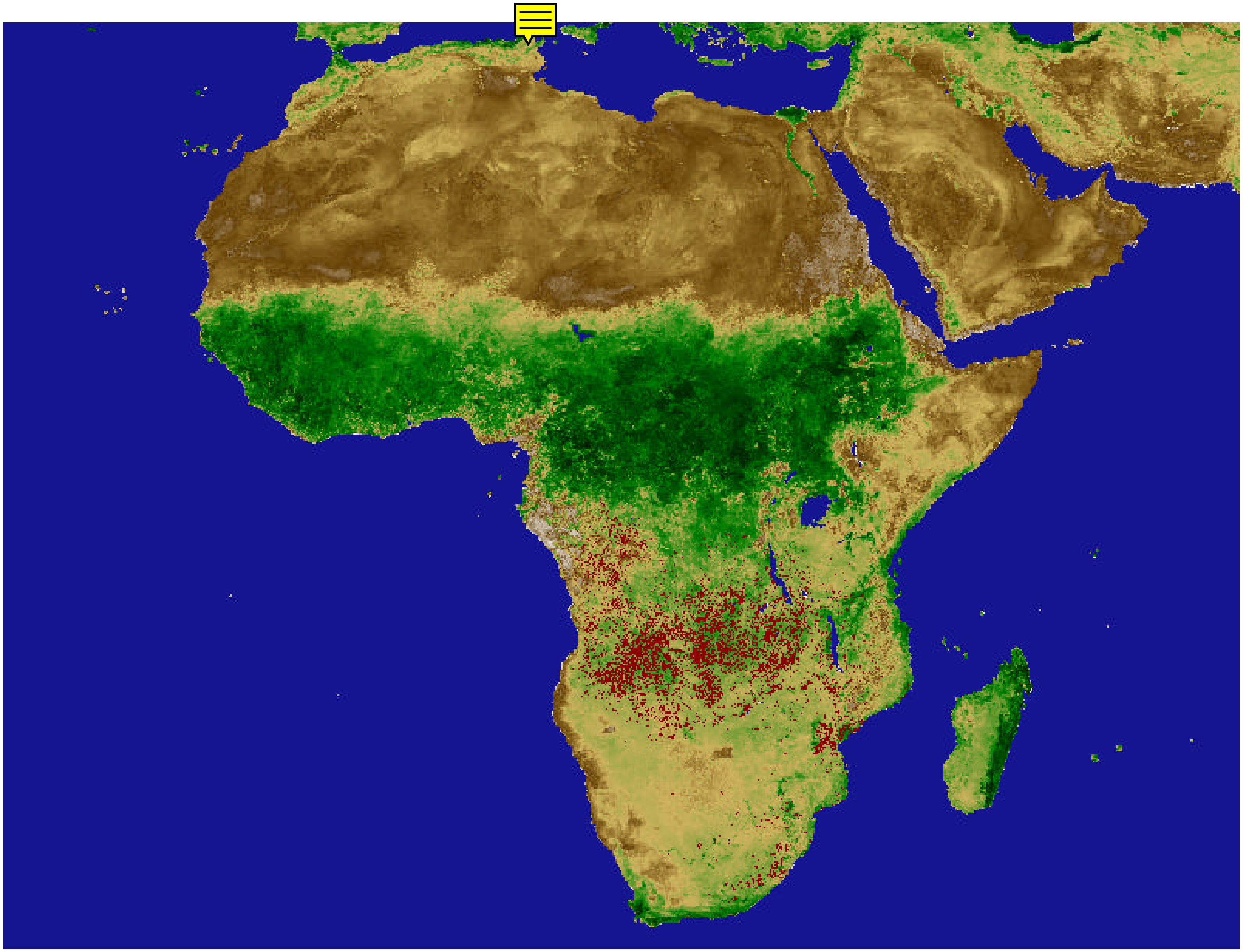
Outgoing Longwave Radiation

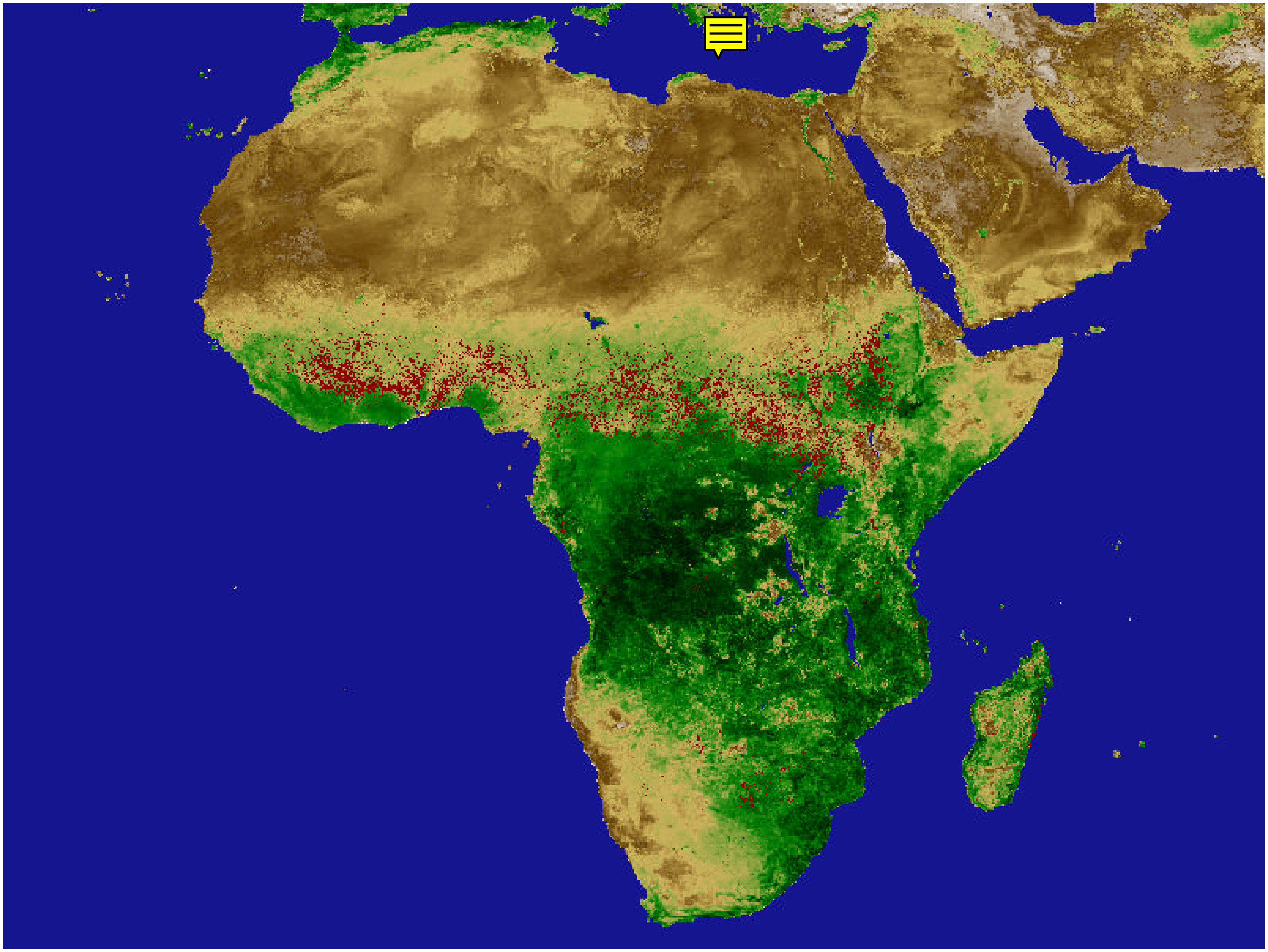
1985-1986

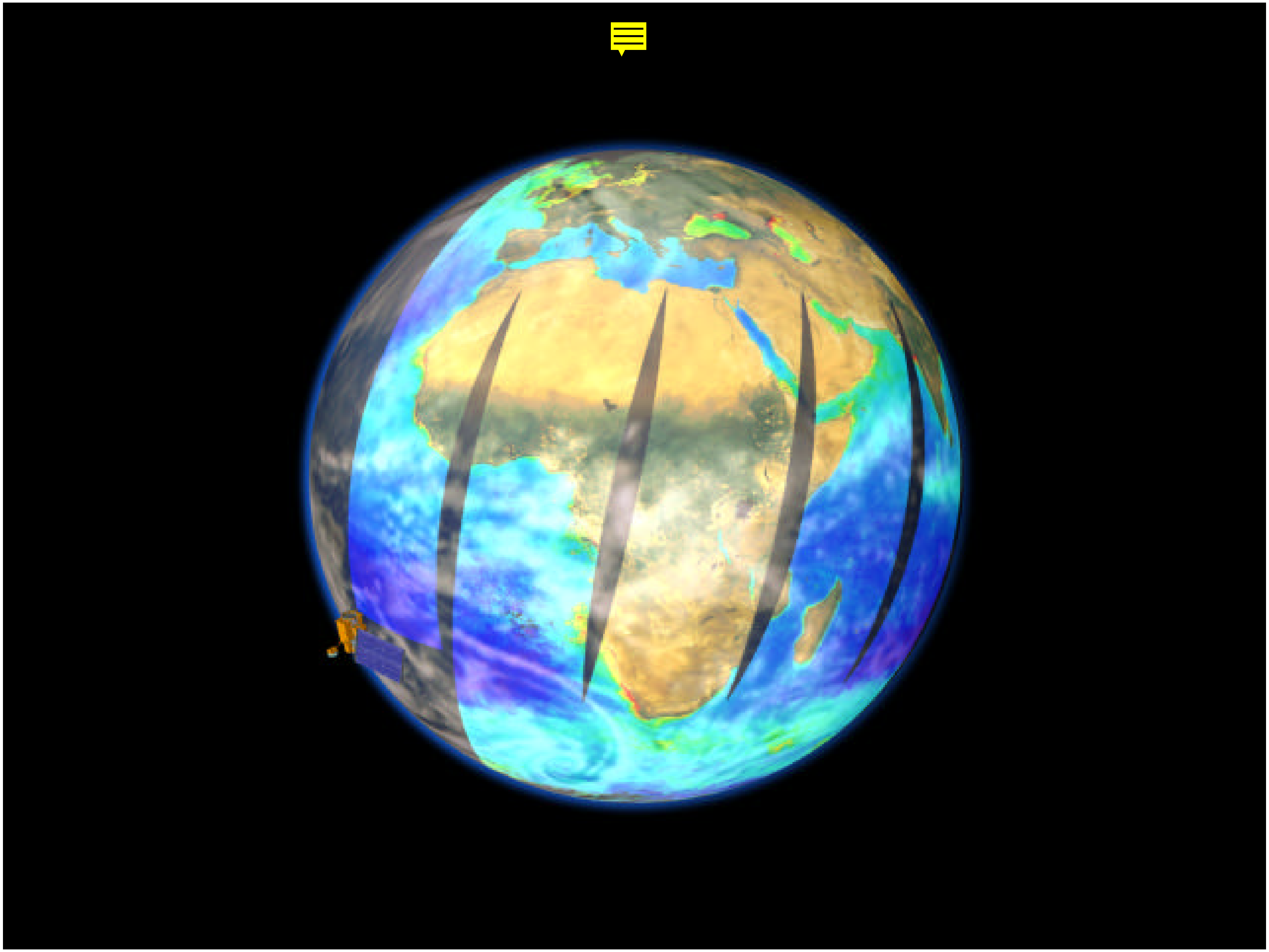


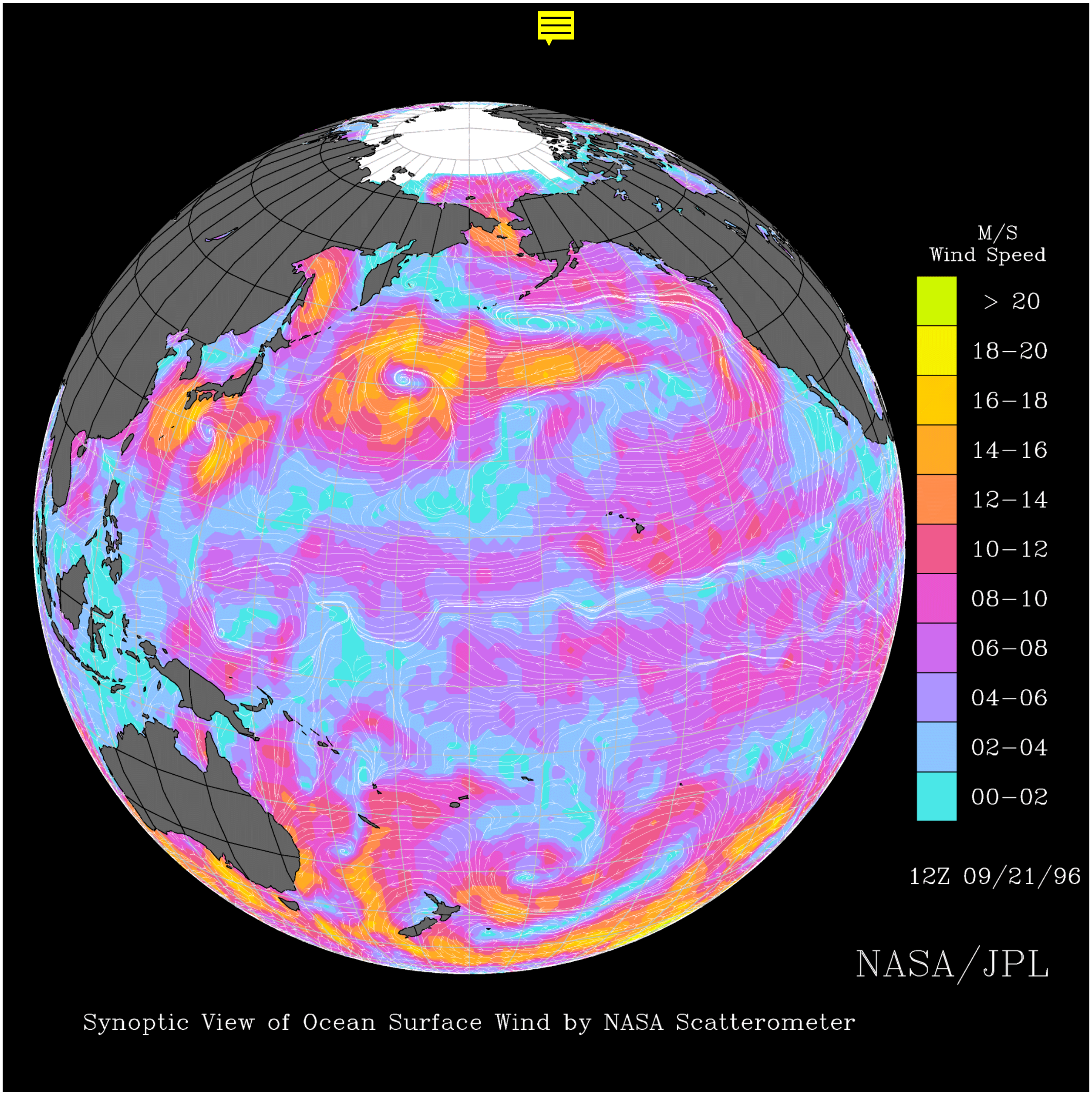











M/S
Wind Speed
> 20
18-20
16-18
14-16
12-14
10-12
08-10
06-08
04-06
02-04
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NASA/JPL
Synoptic View of Ocean Surface Wind by NASA Scatterometer