TECHVIEW: REMOTE SENSING

Terra's View of the Sea

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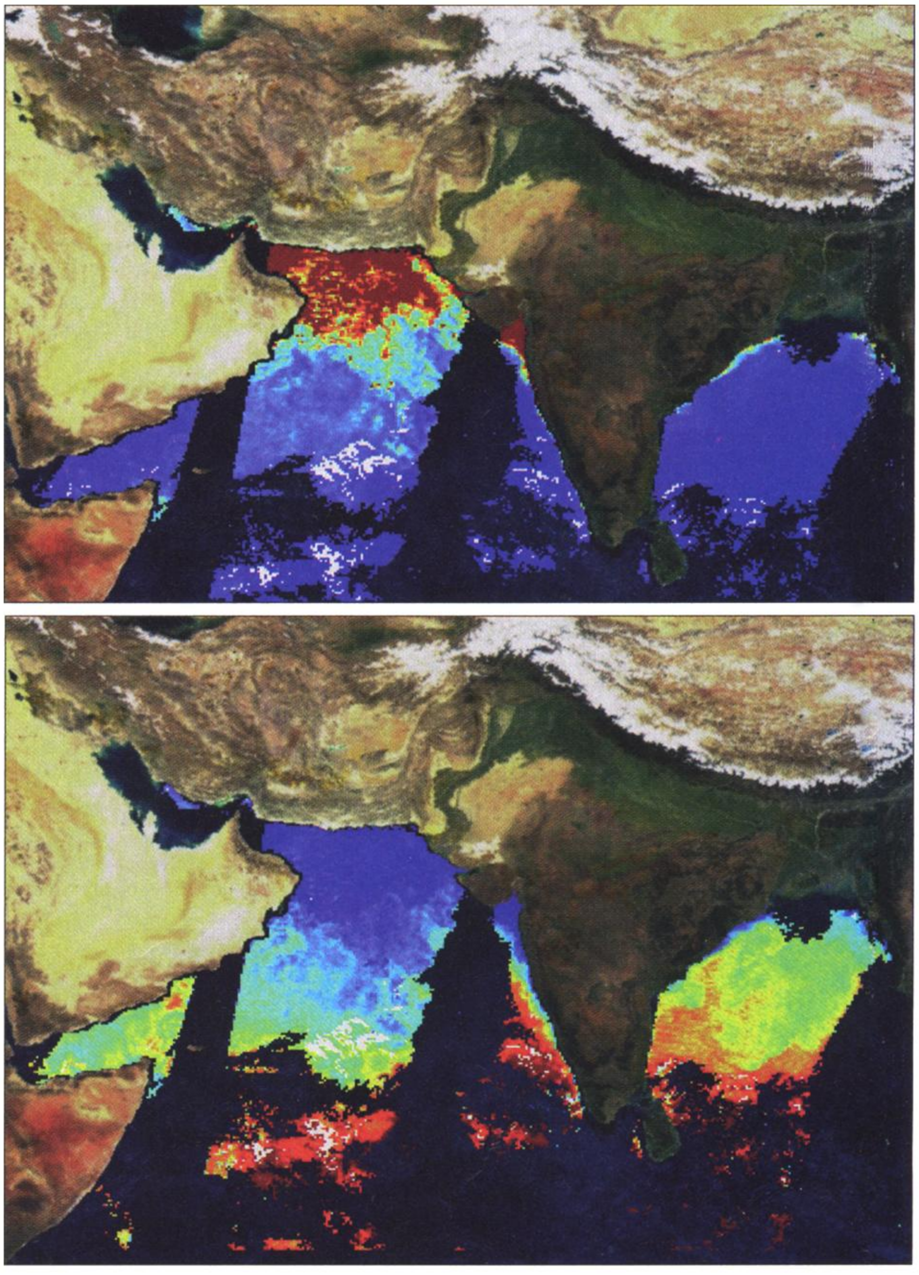
Earth observations from space entered a new phase with the launch of NASA's Terra (formerly known as EOS AM-1) satellite at 1:57 p.m. Eastern Standard Time, 18 December 1999. Terra carries five new remote sensing instruments (*1*) for mapping ocean and land vegetation and productivity patterns, land cover and land use, snow and ice cover, global surface temperatures, cloud properties, water vapor and aerosol properties, and for making other measurements.

Terra is a large and complicated research mission for which planning began more than 15 years ago. It is considered the flagship of NASA's Earth Observing System (EOS) (*2*, *3*), one of a series of Earth observation spacecraft that are to provide observations well into the 21st century. Original plans called for Terra to be one of six similar spacecraft launched during a 15-year period. However, budget problems in the 1990s led to major reductions to NASA's EOS program, and now only two Terra-class spacecraft (EOS PM-1, or "Aqua," will be the second) are planned within EOS (*2*, *4*). Measurement capability of the other four Terra-class spacecraft are to be redistributed among other space platforms, some of which are yet to be determined. Partnerships with other international space agencies and the U.S. National Oceanic and Atmospheric Administration (NOAA) were part of NASA planning in the 1980s and are now essential if EOS is to meet its scientific objectives.

The EOS Science Plan (*4*) encompasses many objectives within the general theme of climate change. Sub-themes focus on Earth's radiation budget (including role of aerosols); ocean circulation, productivity, and ocean-atmosphere exchanges of heat and elements; atmospheric chemistry and greenhouse gases; land ecosystems and hydrology; changes to cryospheric systems; ozone and stratospheric chemistry; and volcanoes and the climate effects of their emissions. The data collection strategy is based on 24 critical observations, most of which are measured, at least to some extent, by Terra (*4*).

Terra's view of the sea comes primarily from Moderate-Resolution Imaging Spectroradiometer (MODIS) (*1*) measurements centered at nine visible/near-infrared (VNIR) and six infrared (IR) wavelengths with approximately 1-km^2 resolution and potential one-day coverage of most of the global ocean (*5*, *6*). VNIR measurements are used to calculate biological and other constituents of ocean waters, including the concentration of chlorophyll a pigment, a measure of microscopic plant (phytoplankton) biomass, the most abundant type of ocean vegetation. Obtaining accurate VNIR measurements of "water-leaving radiance" (sunlight backscattered from ocean waters, or "ocean color") is a major technical challenge because the radiometric signal at spacecraft altitudes is dominated by sunlight backscattered by air molecules and atmospheric aerosols. Extracting the comparatively weak ocean signal, which is less than 10% of the total radiance at visible-band wavelengths from satellite altitudes, requires very high instrument performance as well as accurate



MODIS images of the Indian Ocean. (Upper panel) Phytoplankton chlorophyll a concentration. **(Lower panel)** Ratio of chlorophyll a to chlorophyll a fluorescence. The highest chlorophyll a concentrations (red tones in upper panel) are observed in the nutrient-rich waters of the Arabian Sea. These waters also show highest relative rates of photosynthesis (blue tones in lower panel).

SOURCE: NASA (HTTP://TERRA.NASA.GOV)

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models for molecular and aerosol scattering in the atmosphere (*7*).

IR measurements are used to determine sea surface temperature (SST). The MODIS instrument builds on the experience obtained from previous satellite radiometers, including NOAA's Advanced Very High Resolution Radiometer (AVHRR), to incorporate design innovations that will improve nighttime surface temperature estimates of tropical and subtropical waters (*5*). MODIS VNIR measurements are used to detect and flag cirrus clouds, and also tropospheric and stratospheric aerosols; this is important because both aerosols and cirrus clouds can introduce significant errors in SST measurement from space (*5*). These improvements, together with high-performance specifications at the IR wavelengths, will lead to ocean temperature retrievals with an absolute and relative accuracy of 0.3 to 0.5 kelvin (*4*).

The ocean science objectives for Terra are directly related to understanding the ocean's role in the global carbon cycle and to determining how ocean ecosystems may change in the coming decades as a result of anthropogenic influences. Another key objective is to improve the accuracy and precision of surface ocean-temperature maps, which are a crucial element of climate change studies (*4*). MODIS provides new capabilities for ocean carbon cycle studies and also continues satellite measurements that are used to generate global maps of chlorophyll a concentration in surface waters (*8*). MODIS measurements and analyses will be used to calculate ocean photosynthesis, which is highly variable in time and space (*9*). Other MODIS measurements will be used to derive chlorophyll a fluorescence efficiency (used to estimate the nutritional state or "health" of phytoplankton) (see the figure); the concentrations of colored organic matter (a large but poorly understood ocean carbon pool); the relative amounts of calcifying plankton in surface waters (calcite is also important in the ocean carbon cycle); and the relative abundance of cyanobacteria (photosynthesizing bacteria) (*5*). The ability to measure these properties by remote-sensing should be extremely useful for ocean carbon cycle and large-scale ecosystem studies, but their accuracy needs first to be confirmed by direct comparison with traditional ocean measurements.

The oceans modulate climate through their immense heat storage capability and by redistributing heat between the equator and the poles. SST data are important for calculating air-sea heat exchange, and SSTs play a large role in the coupling between the atmosphere and the ocean (*10*). Achieving the MODIS goal of measuring ocean temperature with 0.3 to 0.5 kelvin absolute accuracy will provide a new capability for the development of a global SST climatology that, over time, will provide direct observations of how climate change affects ocean heat storage (*4*).

MODIS on both Terra and Aqua will provide oceanographers with precise radiometric measurements at VNIR and IR wavelengths. Other EOS sensors will provide radar measurements to study ocean currents, eddies, and wind stress. Passive microwave sensors will also be used to provide all-weather observations of SST as well as measurements of sea ice properties. These are the core satellite measurements required to determine long-term changes in the ocean and its role in global climate. Original EOS plans called for long (15 years or longer) time series of observations, but NASA's de-scoped EOS program needs partners to fly the required sensors. One approach under evaluation is to transfer some of the ocean and other EOS measurements to the U.S. operational satellite program, specifically the National Polar-orbiting Operational Environmental Satellite System (NPOESS). NPOESS began as a combined NOAA and Department of Defense program, which aimed to replace the current generation of U.S. polar-orbiting weather satellites beginning in about 2008. Originally, NASA's role was to provide advanced technology, but it now wants to use NPOESS to extend EOS measurements into the future (*11*). For example, the proposed NPOESS Preparatory Project (NPP) would serve as a "bridge" between Terra and Aqua and the first NPOESS mission. Partnering with the operational satellite program is attractive because it would assure a continuous time series of critical satellite measurements for the foreseeable future. However, the responsibilities for sensor specifications, calibration, product validation, research funding, and other important issues need to be resolved before oceanographers and other members of the scientific community will feel comfortable with the operational satellite program as a primary source of satellite data for climate change and carbon cycle research.

References and Notes

1. These instruments are: MODIS (Moderate-Resolution Imaging Spectroradiometer); MISR (Multi-angle Imaging Spectroradiometer); ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer); MOPITT (Measurements of Pollution in the Troposphere); and CERES (Clouds and the Earth's Radiant Energy System).
2. G. Asrar and R. Greenstone, *MTPE EOS Reference Handbook*, (EOS Project Science Office, NASA/Goddard Space Flight Center, Greenbelt, MD, 1995), pp. 23–27.
3. EOS is a part of NASA's Earth Science Enterprise, formerly called Mission to Planet Earth.
4. M. D. King, Ed., *EOS Science Plan: The State of Science in the EOS Program* (NASA/Goddard Space Flight Center, Greenbelt, MD, 1999).
5. W. E. Esaias *et al.*, *IEEE Trans. Geosci. Remote Sensing* **36**, 1250 (1998).
6. Clouds interfere with VNIR and IR measurements, and thus the effective temporal coverage of a given ocean region depends on the amount of cloud cover. Composite images at 5-day or longer time scales are necessary for a comprehensive global view.
7. H. R. Gordon, *J. Geophys. Res.* **102D**, 17081 (1997).
8. F. P. Chavez *et al.*, *Science* **286**, 2126 (1999).
9. C. B. Field, M. J. Behrenfeld, J. T. Randerson, P. Falkowski, *Science* **281**, 237 (1998).
10. A. E. Gill, *Atmosphere-Ocean Dynamics* (Academic Press, San Diego, CA, 1982) pp. 323–326.
11. H. Jacobowitz, Ed., *Climate Measurement Requirements for the National Polar-orbiting Operational Environmental Satellite System (NPOESS)* (NOAA, Washington, DC, 1997).