FORUM

Carbon Cycle Observations: Gaps Threaten Climate Mitigation Policies

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Successful management of carbon dioxide (CO_2) requires robust and sustained carbon cycle observations. Yet key elements of a national observation network are lacking or at risk. A U.S. National Research Council review of the U.S. Climate Change Science Program earlier this year highlighted the critical need for a U.S. climate observing system to meet requirements of mitigation policies for improved carbon cycle observations. This Forum highlights the most significant gaps and threats to carbon cycle observations—including observations from satellites; in situ observations of land, ocean, and aquatic systems; and direct atmospheric measurements—and suggests ways to improve the U.S. national effort.

Satellite Observations of Land and Oceans Threatened

Since 1972, the Landsat series of satellites has monitored land cover and land use change, classified vegetation, and detected natural disturbances. Landsat enables the quantification of land vegetation and soil carbon fluxes to and from the atmosphere. This continuous series of Earth observations from space is ending as Landsat 5 and 7 deteriorate. Landsat 5 has been operating for 25 years, and both satellites are operating beyond their design lifetimes in degraded status, subject to failure at any time. The Landsat Data Continuity Mission is not scheduled for launch until 2012, leaving open the possibility of 2 or more years of reduced data availability.

Since 2000, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra and Aqua Earth Observing System spacecraft have provided crucial global observations of primary production and vegetation phenology. A continuous record of primary production and phenology started in 1981 with the advanced very high resolution radiometer (AVHRR), the latest of which is still operational, and continues with higher accuracy by MODIS. This record is used in conjunction with ground observations and models to provide regional estimates and maps of carbon stocks and fluxes. The AVHRR-MODIS continuum may be interrupted due to cost overruns and design changes of the National Polar-orbiting Operational Environmental Satellite System (NPOESS), and due to technical problems with the visible infrared imager radiometer suite (VIIRS) instrument, a successor to MODIS. NPOESS (including VIIRS) is not scheduled for launch until 2012 at the earliest, although the NPOESS Preparatory Project will test VIIRS and other sensors aboard a satellite scheduled for launch in 2011.

A continuous ocean color data record dating from 1997 has revealed close relationships between climate variations and ocean biology, with a warming ocean associated with decreased global ocean chlorophyll. New satellite products are emerging (e.g., fluorescence yield, cellular pigment levels) to decipher functional underpinnings of such relationships, but remote sensing of U.S. ocean color capabilities may not continue uninterrupted. Current sensors (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Aqua MODIS) are well beyond their design lifetimes, with SeaWiFS having experienced system failures and significant data gaps in 2008. The continuation of the ocean color climate record will need to rely on the performance of the VIIRS instrument on the NPOESS Preparatory Project and later on NPOESS itself. There is additional concern that VIIRS may not achieve ocean color climate data objectives because cost overruns may force lower specifications for data quality.

Atmospheric Observation Needs Are Rapidly Evolving

For 5 decades, the global network of intercalibrated measurements of atmospheric CO_2 and methane concentrations has been central to climate and carbon cycle studies. These properties reflect the net effect of all global carbon sources and sinks to the atmosphere (anthropogenic, terrestrial, and aquatic). Trace gas measurements (e.g., oxygen, carbon-13, carbon monoxide) indicative of different carbon sources are also obtained at many of the measurement sites. With the current number of active observation sites, the carbon cycle science community is unable to resolve carbon fluxes at spatial scales much smaller than large continents such as North America and at temporal scales shorter than seasonal. Higher-density observations are needed for finer-scale monitoring of carbon sources and sinks and to support verification of the effects of climate change mitigation on the atmosphere. Satellite measurements of atmospheric CO_2 intercalibrated with surface and airborne data have the potential to provide such verification, but the February 2009 failed launch of the NASA Orbiting Carbon Observatory (OCO) mission is a major setback. OCO had the potential to show how spaceborne technologies could be used to monitor greenhouse gas emissions and provide baseline emissions data.

Gaps in Terrestrial Observations and Threats to Continuity

Land-based inventories periodically quantify carbon stocks and fluxes for land and fossil fuel use. However, these inventories do not adequately measure all of the important carbon pools such as soil and dead wood, and they have gaps in geographic and temporal coverage. Forest inventories need to provide improved, timely information on carbon cycle effects of management, harvest rates, land cover changes, productivity rates, and natural disturbances. Harvested carbon and the transport of products also can be significant, but surveys about these are limited. Agricultural, rangeland, and forest inventories need a coordinated and consistent suite of core observations as well as wall-to-wall coverage of biomes and regions currently undersampled, such as Alaskan boreal forests and forested urban areas.

There are large spatial and temporal gaps in soil carbon monitoring, despite soil being the largest terrestrial carbon stock and highly vulnerable to loss from warming. Existing soil classification maps and long-term measurements of soil morphological characteristics do not provide information on dynamic properties (e.g., soil carbon turnover rates). A multiagency-supported network of soil carbon observations, with the capacity for performing measurements over decades and associated with other networks of terrestrial observations, would dramatically improve estimates of soil and ecosystem carbon dynamics at multiple scales.

Direct observations of CO_2 fluxes over decades are necessary to capture terrestrial carbon and water cycle responses to climate variability and to improve carbon and climate system model simulations. The AmeriFlux network, initiated in 1996, includes more than 100 sites observing biological properties; meteorology; and carbon, water, and energy exchanges between terrestrial ecosystems and the atmosphere. Carbon cycle and climate system modelers use these data to characterize terrestrial sources and sinks for carbon, responses of carbon fluxes to climate and land use change, and resulting radiative forcing feedbacks to climate. The continuation of AmeriFlux network observations is essential for understanding long-term trends in response to climate; however, support for AmeriFlux currently is provided on a site-by-site basis, and some long-term, high-quality records are endangered.

Ocean Observations: Insufficient and Lacking Continuity

Ocean ecosystem observations characterize key biological stocks (phytoplankton biomass, functionally related species groups, total particulate and dissolved carbon pools), resolve essential rate processes (photosynthesis, photochemistry), and assess plankton health indices (fluorescence yields, intracellular pigment levels). These observations necessitate technological developments as well as a long-term field observational program allowing for the detection and interpretation of climate-ocean biology impacts and feedbacks.

Ocean carbon field observations attempt to constrain temporal changes in the oceanic inventory, transport, and distribution of inorganic carbon and related biogeochemical species. These observations also characterize the spatial and temporal variability and long-term trends in air-sea CO_2 flux and surface biogeochemistry. Observation programs during the 1990s provided a baseline to detect future changes and also documented anthropogenic CO_2 ocean uptake. Subsequently, the Climate Variability and Predictability (CLIVAR)/CO_2 Repeat Hydrography Program was implemented to maintain decadal time scale sampling of ocean transports and inventories of many climatically significant parameters. However, that program is due to end in 2012. Long-term ocean ecological time series are limited in number. Current sites need to be maintained and augmented with continuous measurements, and new sites and routine surveys need to be established, particularly along North American continental margins.

Aquatic Systems and Terrestrial-Ocean Interfaces Neglected

Rivers and groundwater at the land-ocean margins play a central role in linking terrestrial and marine carbon cycles. Weathering and erosion processes on land; sediment storage within the river system; and transport, transformation, and burial processes in adjacent ocean margins occur at such large magnitudes that they become significant parts of the carbon cycle. Existing research examines the terrestrial as well as the oceanic sinks for organic and inorganic carbon; however, the connections between these two environments are not adequately addressed.

Despite a long history of gauging U.S. rivers and streams, there has been a gradual loss of long-term discharge monitoring stations and a decreased number of annual carbon measurements. Over the past decade, more than 1000 stations out of a total of about 8000—many with more than 30 years of continuous operation—have been lost. These long-term measurements are essential to understanding changes to the hydrologic cycle. Efforts are needed to reinstate stream/river discharge gauging stations, increase the frequency of carbon chemistry sampling, and outfit key gauging stations with high-frequency measurements of carbon pools and indices that inform carbon cycle science and management.

Integrated Approach Needed to Support Climate Policies

Climate and carbon cycle management likely will evolve rapidly in the immediate future, placing new demands on existing observational infrastructure that has gaps and threats to continuity and which is only loosely coordinated. Much of the current observation infrastructure is composed of research data sets that require a transition to operational status to meet future needs, and appropriate agency or interagency leadership and support.

Three major observation systems need improvements and must be well coordinated to support climate policy and management for the remainder of this century: (1) an Earth-observing satellite system that provides continuous measurements of key carbon-related characteristics of the Earth's atmosphere, ocean, and lands; (2) an integrated terrestrial observation system of inventories coupled with a coordinated, permanent network of intensive land and atmosphere monitoring sites; and (3) a long-term, continuous, in situ ocean observation system with appropriate sensors and density of monitoring sites.

The research community is working with U.S. federal agency managers and the U.S. Congress to restore or augment funding to address critical gaps and threats to carbon cycle observations. The design and implementation of a coordinated U.S. observation system must respond to emerging decision support needs, which may be different than requirements of research studies. In addition, the U.S. approach needs to be coordinated with similar efforts around the globe.

This Forum has described the major elements of a U.S. carbon cycle observation system and has highlighted current and potential weaknesses in the system. Climate policies cannot be effective without rigorous tracking and the verification of results. Therefore, we strongly urge U.S. agencies and Congress to carefully consider ways to improve carbon cycle observations as new policies are implemented.

For more information, acknowledgments, and references, please see the electronic supplement to this *Eos* issue (http://www.agu.org/eos_elec/).

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LETTERS

Comment on "On AGU's Position Statement, 'Human Impacts on Climate'"

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Regarding the Forum by Cyril Galvin (*Eos, 89*(46), 459, 2008), while I understand AGU's willingness to present both sides of the coin, as it were, I am disappointed that this Forum appeared in *Eos*.

One major point in question is the assertion by Galvin that "nowhere on the sandy ocean shores of the world is there a beach whose erosion has been documented to be caused by sea level rise." This point disregards the fact that coastal barrier systems have been moving landward for the last several thousand years, driven by rising sea level. Yes, the picture is complex, and yes, wave action and storms, in addition to constraints on sediment supply—many of them heavily influenced in the present day by societal actions—are also important: Some beaches will erode without rising sea level if they are starved of new sediment to replace that removed by wave-driven, alongshore currents, and it is of course the waves that move the sediment around.

However, to give an example of a barrier system driven landward by rising sea level, several thousand years ago, barriers offshore of Martha's Vineyard, Mass., were somewhere between 1 and 2 kilometers offshore (at least that is about as far as it has been possible to track the paleoshoreline using markers from buried organic peats). Under relatively gentle rates of sea level rise, the shoreline retreated at rates that are about an order of magnitude lower than are seen today (parts of the Vineyard's south shore