8

Enhancing Capabilities to Measure and Monitor Greenhouse Gases

The sources of greenhouse gas (GHG) emissions are varied and complex, as are the potential mitigation strategies afforded by advanced climate change technologies presented through this *Plan*. Measurement and monitoring (M&M) systems will be needed to complement these technologies to assess their efficacy and sustainability and to guide future research and enhancements. Contributing M&M systems cover a wide array of GHG sensors, instrumentation, measurement platforms, monitoring and inventorying systems, and associated analytical tools, including databases, models, and inference methods.

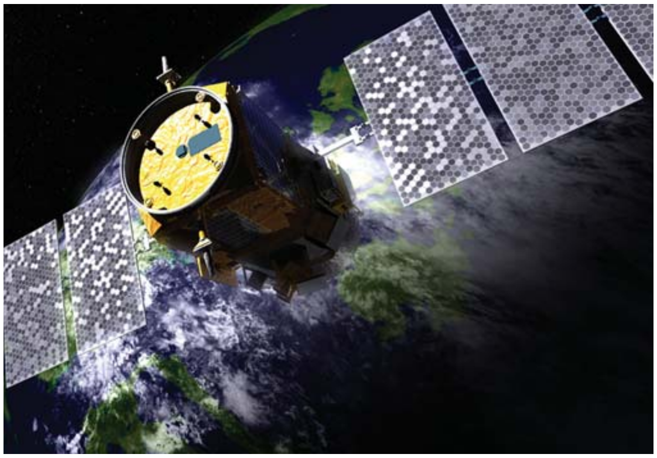

Figure 8-1. Earth observation activities benefit both CCSP and CCTP research. For example, satellites such as CALIPSO (pictured above) take measurements of natural processes using advanced techniques such as Light Detection and Ranging (LIDAR). These measurements can be used in atmospheric research and, for CCTP, to help scientists estimte emissions reductions in energy end-use, energy supply, sequestration, and non-CO_2 gases.

Credit: NASA

Development and application of such systems can provide accurate characterizations of GHG emissions from both existing and advanced technologies, enable increased understanding of performance, guide further research, reduce costs, and improve effectiveness. Research on and development of these systems is required to increase their capabilities and facilitate and accelerate their adoption (Figure 8-1).

Observations using M&M technologies can be used to establish informational baselines necessary for analytical comparisons, and to measure carbon storage and GHG fluxes across a range of scales, from individual locations to large geographic regions. If such baselines are established, the effectiveness of implemented GHG-reduction technologies can be assessed against a background of prior or existing conditions and other natural indicators. Many of the M&M technologies and the systems they can enable benefit from the ongoing R&D under the aegis of the Climate Change Science Program (CCSP), and from other Earth observation activities that are underway. All such M&M systems constitute an important component of a comprehensive Climate Change Technology Program (CCTP) R&D portfolio and could be improved through further development as outlined below.

On February 16, 2005, 55 countries endorsed a 10-year plan to develop and implement the Global Earth Observation System of Systems (GEOSS) for the purpose of achieving comprehensive, coordinated, and sustained observations of the Earth system. The U.S. contribution to GEOSS is the Integrated Earth Observation System (IEOS). IEOS will meet U.S. needs for high-quality, global, sustained information on the state of the Earth as a basis for policy and decision-making in every sector of society. A strategic plan for IEOS[1] was developed by the United States Group on Earth Observation (USGEO), a Subcommittee reporting to the National Science and Technology Council's Committee on Environment and Natural Resources; the plan was released in April 2005. Both the GEOSS and the IEOS are focused on societal benefits, including climate variability and change, weather forecasting, energy resources, water resources, land resources, and ocean resources—all of which are relevant to CCSP and CCTP.

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[1] Accessible at http://iwgeo.ssc.nasa.gov

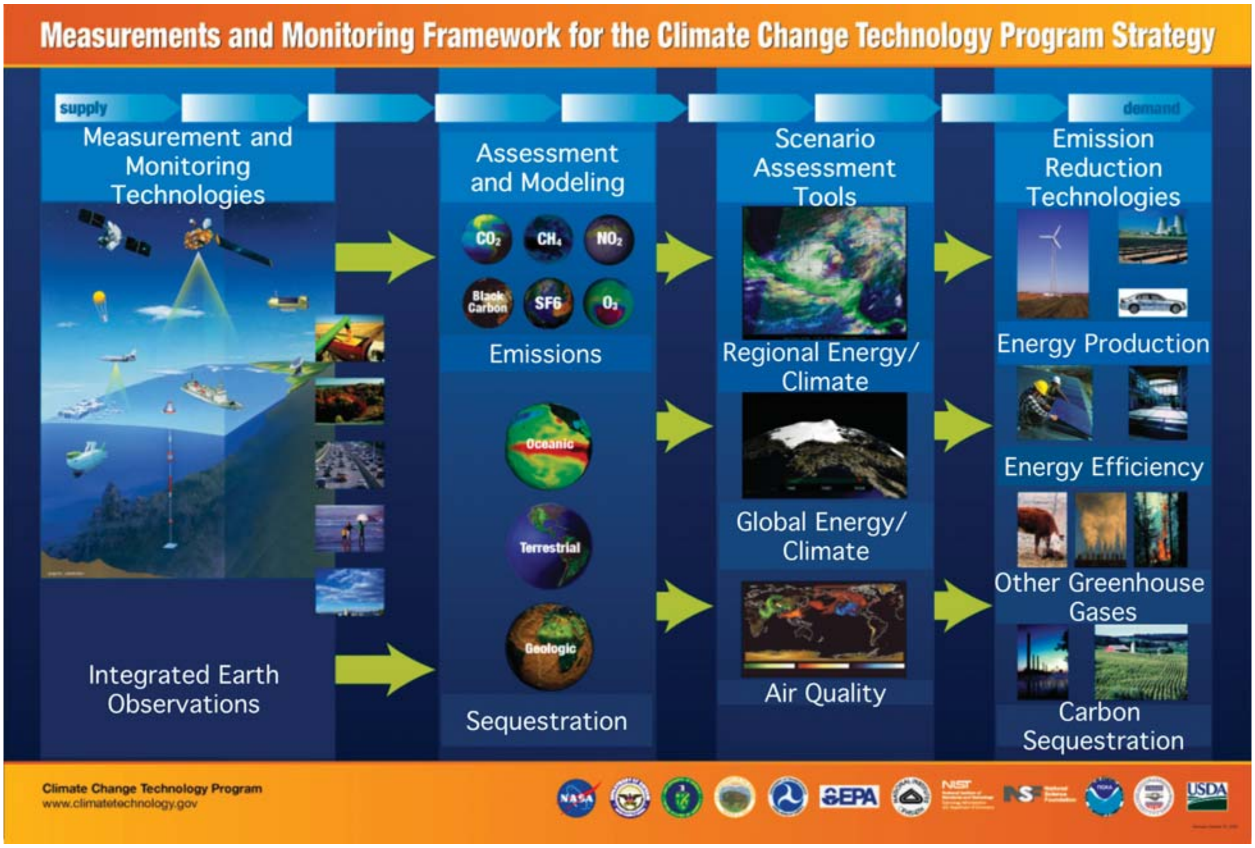
8.1 Potential Role of Technology

M&M systems are important to addressing uncertainties associated with cycling of GHGs through the land, atmosphere, and oceans, as well as in measuring and monitoring GHG-related performance of various existing and advanced climate change technologies. R&D in this area offers the potential to:

- Characterize emissions, inventories, concentrations, and cross-boundary fluxes of carbon dioxide (CO_2) and other greenhouse compounds, including the size and variability of the fluxes.
- Characterize the efficacy and durability of particular mitigation technologies or other actions, and verify and validate claims for results.
- Measure (directly or indirectly through proxy measurements) anthropogenic changes in sources and sinks of GHGs and relate them to causes, to better understand the role of various technologies and strategies for mitigation.
- Identify opportunities and plans for guiding research investments in GHG M&M methods, technologies, and strategies.
- Explore relationships among changes in GHG emissions, fluxes, and inventories due to changes in surrounding environments.
- Optimize the efficiency, reliability, and quality of M&M that maximizes support for understanding and decision-making while minimizing the transaction costs of mitigation activities.

Ideally, an integrated observation system strategy would be employed to measure and monitor the sources and sinks of all gases that have an impact on climate change, using the most cost-effective mix of techniques ranging from local *in situ* sensors to global

Measurement and Monitoring Technologies for Assessing the Efficacy, Durability, and Environmental Effects of Emission Reduction and Stabilization Technologies



Measurements and Monitoring Framework for the Climate Change Technology Program Strategy

supply

demand

Measurement and Monitoring Technologies

Integrated Earth Observations

Assessment and Modeling

Emissions

Sequestration

Scenario Assessment Tools

Regional Energy/ Climate

Global Energy/ Climate

Air Quality

Emission Reduction Technologies

Energy Production

Energy Efficiency

Other Greenhouse Gases

Carbon Sequestration

Climate Change Technology Program
www.climatetechnology.gov

Figure 8-2. Measurement and Monitoring Technologies for Assessing the Efficacy, Durability, and Environmental Effects of Emission Reduction and Stabilization Technologies remote-sensing satellites. This would involve technologies aimed at a spectrum of applications, including CO_2 from energy-related activities (such as end use, infrastructure, energy supply, and CO_2 capture and storage) and GHGs other than CO_2 (including CH_4, N_2O, fluorocarbons, ozone, and other GHG-related substances, such as black carbon [BC] aerosol). An integrating system architecture serves as a guide for many of the step-by-step development activities required in these areas. It establishes a framework for R&D that places M&M technologies in context with the Integrated Earth Observation System (IEOS) and other CCTP technologies (Figure 8-2). The integrated systems approach provides feedback through which demand-side actors (both in the public and private sectors) contribute to benchmarking results against expectations.

Such a framework facilitates coordinated progress evolving over time toward increasingly effective solutions and common interfaces of the gathered data and assessment systems. An integrating architecture would function within the context of, and in coordination with, other Federal programs (e.g., CCSP and the U.S. Group on Earth Observations) and international programs (e.g., the World Meteorological Organization and the Intergovernmental Panel on Climate Change) that provide or use complementary M&M capabilities across a hierarchy of temporal and spatial scales. It could, therefore, take advantage of the synergy between observations to measure and monitor GHG mitigation strategies and the research on observation systems for the CCSP, as well as the operational observations systems for weather forecasting, as described more fully in the CCTP report, *Technology Options for the Near and Long Term* (CCTP 2003).

In the near term, opportunities for advancing GHG measuring and monitoring systems present themselves as integral elements of the CCTP R&D programs and initiatives. Efforts must focus on the significant emission sources and sinks and on M&M of carbon sequestration and storage.

Technology can be developed to address knowledge gaps in GHG emissions and to improve inventories. In some cases, it is not necessary or cost-effective to measure emissions directly. In such cases, emissions can be measured indirectly by measuring other parameters as proxies, such as feedstock, fuel, or energy flows (referred to as "parametric" or "accounting-based" estimates); or by measuring changes in carbon stocks. Under CCTP, there is a benefit to undertaking research to test, validate, quantify uncertainties, and certify such uses of proxy measurements.

The long-term approach is to evaluate data needs and pursue the development of an integrated and overarching system architecture that focuses on the most critical and supplementary data needs. Common databases would provide measurements for models that could estimate additions to and removals from various GHG inventories, forecast the long-term fates of various GHGs, and integrate results into relevant decision support tools and global-scale monitoring systems. This approach would include protocols for calibrated and interoperable (easily exchanged) data products, emissions accounting methods development, and coordination of basic science research in collaboration with CCSP. Tools would be validated by experimentation to benchmark protocols (to quantify the improvements that the tools provide), so that they would be recognized and accepted by the community-of-practice for emissions-related processes.

The M&M technologies that are emphasized in the following sections are based on their capacity to address one or more of the following criteria:

- M&M technology that supports the successful implementation and validation of a technological option that mitigates a substantial quantity of U.S. GHG emissions, on the order of a gigaton of carbon equivalent or more, over the course of a decade.
- M&M technology capacity to reduce a key uncertainty associated with a mitigation option.
- M&M technology sufficiently differentiated from, or adequately integrated with, comparable research efforts in the CCSP, IEOS, or other operational Earth observation systems.
- M&M technology helping to assure that a proposed advanced climate change technology does not threaten either human health or the environment.

8.2 Energy Production and Efficiency Technologies

M&M systems provide the capability to evaluate the efficacy of efforts to reduce GHG emissions through the use of (1) low-emission fossil-based power systems; (2) potentially GHG-neutral energy supply technologies, such as biomass energy systems (see Chapter 6) and other renewable energy technologies, including geothermal energy; and (3) technologies to more efficiently carry and/or transmit energy to the point of use. In this section, the M&M R&D portfolio for energy production and efficiency technologies is presented. Each of these technology sections includes a sub-section describing the current portfolio. The technology descriptions include a link to an updated version of the CCTP report, *Technology Options for the Near and Long Term*.[2]

Technology Strategy

M&M technologies can enhance and provide direct and indirect emissions measurements at point and mobile sources of GHG emissions. "Point sources" range from electric generation plants to industrial facilities. The term "mobile sources" typically refers to vehicles. Table 8.1 summarizes the nature of point and mobile sources and the potential roles for M&M technologies, which are broadly applicable across the range of emission sources and scales. The technology strategy emphasizes the potential role of M&M technologies in applications across a range of scales, from the individual vehicle to the larger power plant or industrial facility, as well as the balance between those M&M technologies needed in both the near- and long-terms. Development of software and tools that facilitate further integration of measurement data with emission modeling processes is a key dimension of the overall technology strategy. In the near term, the strategy focuses on technologies that measure multiple gases across spatial dimensions. In the long-term, the strategy focuses on development and evolution of a system of systems for remote, continuous, and global M&M that facilitates emissions accounting from the local to the global level.

Proposed R&D Portfolio for Measurement and Monitoring of Energy Production and Use Technologies

GHG EMISSION SOURCE	NATURE OF EMISSIONS AND SCALE	R&D PORTFOLIO OF MEASUREMENT AND MONITORING TECHNOLOGY
Power Generation	Large point sources	Component and system-level technologies to enable and demonstrate direct measurements, continuous emission monitoring, on-board diagnostics, remote sensing, data transmission and archiving, inventory-based reporting, and decision-support systems.
Industrial Facility	Many different processes, but mostly point sources	As above.
Transportation	Many mobile sources widely distributed	As above.

Table 8-1. Proposed R&D Portfolio for Measurement and Monitoring of Energy Production and Use Technologies

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[2] The full report is available at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

Current Portfolio

R&D programs for M&M technologies spanning the Federal complex are focused on a number of areas, including the following:

- High-temperature sensors for NO_X and ozone, ammonia, and other gas emissions, with application in caustic industrial environments (e.g., steel mills, pulp and paper industries);
- Fast-response mass spectrometers and field-deployable isotope analysis systems;
- Continuous emissions monitors (CEMs) for measuring multiple gases at point sources (linked with energy use statistics at a facility); and
- Light Detection and Ranging (LIDAR) for remote monitoring of truck and aviation emissions.

The overall goals are to develop sensors and data transmission systems that allow quantification of emission reductions resulting from energy efficiency improvements.[3]

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

- Improvements in performance, longevity, autonomy, spatial resolution of measurements, and data transmission of CEMs with the ability to measure multiple gases.
- More thorough process knowledge and life-cycle analysis for the estimation of changes in emission factors as a function of time and process.
- Satellite-based sensors for direct measurement of CO_2 and other gases or indicators, tracers, and isotopic ratios.
- Inexpensive, large-area systems for monitoring CO_2 leaks from energy production and end use.
- Low-cost, multiple wireless micro sensor networks to monitor migration, uptake, and distribution patterns of CO_2 and other GHGs in soil and forests.
- Data protocols and analytical methods for producing and archiving specific types of data to enable interoperability and long-term maintenance of data records, data production models, and emission coefficients that are used in estimating emissions.
- Protocols and concurrent technologies for multiple assessments of the performance of end-uses of energy, including transportation, buildings, and industry. Assessments could ultimately provide real-time feedback to the end user.
- Direct measurements to replace proxies and estimates when these measurements are more cost-effective to optimize emissions from sources and improve understanding of the processes behind the formation of GHGs.

8.3

CO_2 Capture and Sequestration

As discussed in Chapter 6, capture, storage, and sequestration of CO_2 can be accomplished by various approaches, including capture from point sources, accompanied by geologic or oceanic storage; and terrestrial sequestration. Advanced technologies can make significant contributions to measuring and monitoring GHG emissions that are captured, stored, and sequestered.

Innovations to assess the integrity of geologic structure, leakage from reservoirs, and accounting of sequestered GHGs are useful. Also useful are integrated carbon sequestration measurements of different components (geologic, oceanic, and terrestrial) across a range of scales and time, from the point of use at the present time to regional or larger scales over the future to provide a consistent net accounting of GHG inventories, emissions, and sinks. Advanced M&M technologies can provide histories of CO_2 concentration profiles near the sites of sequestration and track the potential release of CO_2 into the atmosphere. The development of software and tools that facilitate further integration of measurement data with emission modeling processes play an important, ongoing role in the M&M of sequestered CO_2 in conjunction with other technologies. Different M&M strategies associated

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[3] For more details on the current R&D activities, see CCTP (2005): http://www.climatetechnology.gov/library/2005/tech-options/index.htm.

with the three alternative storage and sequestration approaches are described in the following sections.

Geologic Sequestration

M&M technologies are useful to assess the performance and efficacy of geologic storage systems. They will be critically important in assessing the integrity of geologic structures, transportation, and pipeline systems, the potential of leakage of sequestered GHGs in geologic structures, and in fully accounting for GHG emissions.

Technology Strategy

Realizing the possibilities of these technologies is the focus of a research portfolio that embraces a combination of M&M technologies for separation and capture, transportation, and geologic storage. In the near term, technologies can be improved to measure efficacy of separation and capture, and the integrity of geologic formations for long-term storage. Within the constraints of available resources, a balanced portfolio addresses the objectives shown in Table 8-2.

Proposed R&D Portfolio for Measurement and Monitoring Systems for Geologic Sequestration

SYSTEM CONCEPTS	R&D PORTFOLIO
Separation and Capture	• Monitors for CO_2 emissions using process knowledge • Sensors to monitor fugitive emissions around facilities
Transportation	• Leak detection systems from pipelines and other transportation • Pressure transducers • Remote detectors • Gaseous tracers enabling remote leakage detection
Geologic Storage	• Detectors for surface leakage • Indicators of leakage based on natural and induced tracers • Seismic/electromagnetic/ electrical resistivity/pressure monitoring networks

Table 8-2. Proposed R&D Portfolio for Measurement and Monitoring Systems for Geologic Sequestration

Current Portfolio

Recent progress has been made in developing M&M technologies for geologic carbon sequestration. Many technologies for monitoring and measuring exist today. However, they may need to be modified to meet the requirements of CO_2 storage. The goals are to develop the ability to assess the continuing integrity of subsurface reservoirs using integrated system of sensors, indicators, and models; improve leak detection from separation and capture pipeline systems; apply remote sensors to fugitive emissions from reservoirs and capture facilities; improve, develop, and implement tracer addition and monitoring programs; evaluate microbial mechanisms for monitoring and mitigating diffuse GHG leakage from geologic formations; and more.[4]

Both surface and subsurface measurement systems for CO_2 leak detection and reservoir integrity estimates have been employed at sites currently storing CO_2. Large M&M efforts have taken place at Weyburn, Alberta, and at Sleipner in the North Sea. Within the measurement systems employed at these sites, seismic imaging using temporal analyses of 3-dimensional (3D) seismic structures (called 4D seismic analyses) have been commonly employed to characterize the reservoir, determine changes in reservoir structure and integrity, and to determine locations of CO_2 that have been pumped downhole. At the Sleipner site, for example, efforts to quantify the CO_2 have been undertaken through 4D seismic research. Other methods of subsurface reservoir analyses are cross-well seismic tomography, passive and active doublet analyses, microseismic analyses, and electromagenetic analyses.

Leak detection of CO_2 from storage reservoirs has been performed in the subsurface and surface regions. Within the subsurface, groundwater chemistry, precipitation of calcite, and subsurface CO_2 concentration measurements have been used to detect small gas emissions from reservoirs. At the ground surface, CO_2 flux changes, isotopes of CO_2 and other tracers, and vegetation changes have been monitored to detect surface leaks of CO_2 and identify the source.

Specific examples include four ongoing experiments: (1) Seismic methods are being used at the Sleipner test site to map the location of CO_2 storage;

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[4] For more information on the current R&D activities, see Section 5.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-53.pdf.

(2) Models, geophysical methods, and tracer indicators are being developed through the GEO-SEQ project (Box 8-1); (3) Detection of CO_2 emissions from natural reservoirs has been investigated by researchers at the Colorado School of Mines, University of Utah, and the Utah Geological Survey, including isotopic discrimination of biogenic CO_2 from magmatic, oceanographic, atmospheric, and natural gas sources; and (4) Fundamental research on high-resolution seismic and electromagnetic imaging and on geochemical reactivity of high partial-pressure CO_2 fluids is being conducted.

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

- Tying the experimental research to the process models for geological storage systems, where fate and transport of the stored CO_2 are measured and verified with models. This contributes to verification of CO_2 storage in geologic structures in both the near- and long terms.
- The ability to assess the continuing integrity of subsurface reservoirs using an integrated system of sensors, indicators, and models. The heterogeneity of leakage pathways and probable changes over time make detection and quantification difficult.
- Indicators such as seismic, electromagnetic imaging, and tracers are needed for quantitative determination of CO_2 stored and specific locations of where the CO_2 is located underground.
- Improvements in leak detection from separation and capture and pipeline systems. Low leakage rates occurring at spatially separated locations make full detection difficult.

BOX 8-1

GEOLOGICAL SEQUESTRATION OF CARBON DIOXIDE

(GEO-SEQ) is a comprehensive program examining a range of issues that include cost optimization, monitoring, modeling, and capacity estimation, associated with CO_2 sequestration in geological formations. The GEO-SEQ Project is a public-private applied R&D partnership, formed with the goal of developing the technology and information needed to enable safe and cost-effective geologic sequestration by the year 2015. The effort, supported by DOE and involving several of its national laboratories, as well as universities and industry, conducts applied research and development to reduce the cost and potential risk of sequestration, as well as to decrease the time to implementation. See DOE-NETL (2004).

Terrestrial Sequestration

Sequestering carbon in terrestrial ecosystems (forests, pastures, grasslands, croplands, etc.) increases the total amount of carbon retained in biomass, soils, and wood products. Methods used to measure and monitor terrestrial sequestration of carbon should address both the capture and retention of carbon in both above- and below-ground components of ecosystems. Determining measures of the desired levels of net sequestration will depend on evaluation of GHG emissions as a function of management practices and naturally occurring environmental factors (Post et al. 2004).

Technology Strategy

M&M systems employ an R&D portfolio that provides for integrated, hierarchical systems of ground-based and remote-sensing technologies of different system components over a range of scales. A system's utility is based on its applicability to a wide range of potential activities and a very diverse land base, an accuracy that satisfies reporting requirements of the 1605(b) voluntary reporting program (EIA 2004), and a cost of deployment such that M&M does not outweigh the value of the sequestered carbon. A balanced portfolio should address
(1) remote sensing and related technology for land-cover and land-cover change analysis, biomass and net-productivity measurements, vegetation structure, etc.; (2) low-cost, portable, rapid analysis systems for *in situ* soil carbon measurements; (3) flux measurement systems; (4) advanced biometrics from carbon inventories; and (5) carbon and nutrient sink/source tracing and movement, including using

isotope markers; and (6) analysis systems that relate management practices (e.g., life-cycle wood products, changes in agriculture rotations, energy use in ecosystem management, and others) to net changes in emissions and sinks over time (e.g., changes in agriculture rotations, energy use in ecosystem management, and others).

Current Portfolio

Current research activities associated with terrestrial sequestration are found across a number of Federal agencies. The goals of the current activities are to provide an integrated hierarchical system of ground-based and remote sensing for carbon pools and CO_2 and other GHG flux measurements; reduce uncertainty on regional-to-country scale inventories of carbon stocks; develop low-cost, portable, rapid analysis systems for *in situ* soil carbon measurements; and develop standard estimates that relate management practices to net changes in emissions/sinks over time.[5]

The current portfolio includes the following:

- The Environmental Protection Agency (EPA), with assistance from the U.S. Department of Agriculture's (USDA) Forest Service, prepares national inventories of emissions and sequestration from managed lands. These inventories capture changes in the characteristics and activities related to land uses, and are subject to ongoing improvements and verification procedures.
- The USDA Forest Service Forest Inventory and Analysis Program and the Natural Resources Conservation Service's National Resources Inventory provide baseline information to assess the management, structure, and condition of U.S. forests, croplands, pastures, and grasslands. This information is then converted to State, regional, and national carbon inventories. Hierarchical, integrated monitoring systems are being designed in pilot studies such as the Delaware River Basin interagency research initiative.
- Prototype soil carbon analysis systems have been developed and are undergoing preliminary field testing.

BOX 8-2

AGRIFLUX

The Agriflux network is being developed by the USDA to measure the effects of environmental conditions and agricultural management decisions on carbon exchange between the land and the atmosphere. The network now comprises more than 125 sites in North and South America. Studies will identify crop management practices to optimize crop yield, crop quality, and carbon sequestration and other environmental conditions. Research will lead to new ways for prediction and early detection of drought in agricultural systems based on weekly and monthly climate forecasts.

BOX 8-3

AMERIFLUX

Courtesy of DOE

Flux towers such as the one pictured above are taking long-term measurements of CO_2 and water vapor fluxes in over 250 sites throughout the world, including the United States. Data gathered from these measurement sites are important to understanding interactions between the atmospheric and terrestrial systems. The network (http://public.ornl.gov/ameriflux/) is part of an international scientific program of flux measurement networks (e.g., FLUXNET-Canada, CarboEurope, and AsiaFlux) that seeks to better understand the role of the terrestrial biosphere carbon cycle. See http://www.fluxnet.ornl.gov/fluxnet/index.cfm for a global listing of flux towers.

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[5] For a detailed discussion on technologies and current research activities, see
Section 5.4 http://www.climatetechnology.gov/library/2005/tech-options/tor2005-54.pdf,
Section 3.2.3.1 http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3231.pdf, and
Section 3.2.3.2 http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3232.pdf (CCTP 2005).

- Methods are being developed for the use of Synthetic Aperture Radar in estimating forest bole volume at landscape scale.
- Satellite and low-altitude remote sensing systems have been developed that can quantify agricultural land features at spatial resolution of approximately 0.5 square meters and measure indicators of the carbon sequestration capacity of land use.
- Prototype versions of web-based tools are being developed for estimating carbon budgets for regions (e.g. CASA/CQUEST, CENTURY)
- Multidisciplinary studies are providing increased accuracy of carbon sequestration estimates related to land management and full accounting of land/atmosphere carbon exchange.
- The Agriflux and AmeriFlux programs (Boxes 8-2 and 8-3) are being implemented to improve the understanding of carbon pools and fluxes in large-scale, long-term monitoring areas. The flux measurements provide quantitative data for calibrating/validating remote sensing and other estimates of carbon sequestration. Approaches for scaling these results to regional estimates are under development (DOE-ORNL 2003).
- Other aerospace research activities focusing on imaging and remote sensing methods include LIDAR and RADAR, used for 3D imaging of forest structure for the estimation of carbon content in standing forests.
- Isotopes are being used to assess sequestration potentials by monitoring fluxes and pools of carbon in natural ecosystems.
- Increased accuracy of carbon sequestration estimates is being accomplished for use in land management and full carbon accounting procedures.
- Ongoing tillage and land conservation practices offer test beds for ground-based and remote-sensing methods, as well as verification of rules-of-thumb for emission factors.
- Many of the DOE National Laboratories are conducting research on *in situ* and remote-sensing technologies and laser-based diagnostics, supported by a variety of Federal agencies. These diagnostics include microbial indicators, Laser Induced Breakdown Spectroscopy (LIBS), LIDAR, Fourier Transform Infrared (FTIR) Spectroscopy, and a variety of satellite Earth observation programs (Box 8-4).

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future

BOX 8-4

DIAGNOSTIC TECHNOLOGIES

Laser Induced Breakdown Spectroscopy (LIBS) is a robust chemical analysis technique that has found application in a range of areas where rapid, remote, and semi-quantitative analysis of chemical composition is needed. The technique in its essential form is quite simple. Light is used to ionize a small portion of the analyte and the spectral emission (characteristic of the electronic energy levels) from the species in the resulting plasma is collected to determine the chemical constituents. Most often the light comes from a laser since high-photon fluxes can be obtained readily with this type of light source. By focusing the light from the laser to a small spot, highly localized chemical analysis can be performed.

LIght Detection and Ranging (LIDAR) uses the same principle as RADAR. The LIDAR instrument transmits light out to a target. The transmitted light interacts with and is changed by the target. Some of this light is reflected/ scattered back to the instrument where it is analyzed. The change in the light properties enables some property of the target to be determined. The time for the light to travel out to the target and back to the LIDAR is used to determine the distance to the target.

Fourier Transform Infrared Spectroscopy (FTIR) technology has the capability to measure more than 100 of the 189 Hazardous Air Pollutants (HAPs) listed in Title III of the Clean Air Act Amendments of 1990. FTIR has the capability of measuring multiple compounds simultaneously, thus providing an advantage over current measurement methods, which measure only one or several HAPs. FTIR provides a distinct cost advantage since it can be used to replace several traditional methods.

research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

- Further development of imaging and volume-measurement sensors for land use/land cover and biomass estimates.
- Development of low-cost, practical methods to measure net carbon gain by ecosystems, and life cycle analysis of wood products, at multiple scales of agriculture and forest carbon sequestration.
- Research on isotope markers to identify and distinguish between natural and human sources and determine movement of GHGs in geological, terrestrial, and oceanic systems.
- Identification of new measurement technology needs that support novel sequestration concepts such as enhanced mechanisms for CO_2 capture from free air, new sequestration products from genome sequencing, and modification of natural biogeochemical processes.

Oceanic Sequestration

Sequestering carbon in oceans generally refers to two techniques: direct injection of CO_2 to the deep ocean waters, and fertilization of surface waters with nutrients. For direct injection, CO_2 streams are separated, captured, and transported using processes similar to those for geologic sequestration, and injected below the main oceanic thermocline (depths of greater than 1,000 to 1,500 meters). Fertilization of the oceans with iron, a nutrient required by phytoplankton, is a potential strategy to accelerate the ocean's biological carbon pump and thereby enhance the draw down of CO_2 from the atmosphere. For a description of oceanic sequestration approaches, see Section 6.4 in Chapter 6.

Measuring and monitoring technologies associated with CO_2 injection are directed towards the performance of the quantities of CO_2 injected and dispersion of the concentrated CO_2 plume. M&M technologies associated with ocean fertilization are focused on the quantity of carbon exported deeper in the water column and the stability and endurance of the carbon sink. Carbon sequestration in oceans can be enhanced significantly, but this has yet to be demonstrated, and the environmental impact of such an approach has not been fully evaluated.

Technology Strategy

These technologies could be advanced through R&D in direct measurement and model analysis, as well as indirect indicators that can be used across spatial scales for obtaining process information and for ocean-wide observations. In the near term, possible advances include (1) measurement of comprehensive trace gas parameters (total CO_2, total alkalinity, partial pressure of CO_2, and pH) to monitor the CO_2 concentration in seawater; (2) development of indirect indicators of fertilization effectiveness using remote-sensing technology; and (3) development of CO_2 sensors that "track" the dissolved CO_2 plume from injection locations. In the long term, advances could include a system that monitors CO_2 in the oceans, temporally and spatially, using integrated M&M concepts, satellite-based sensors, and other analysis systems that can avoid costly ship time.

Current Portfolio

The goal of the current research in support of M&M technologies associated with ocean sequestration is to develop integrated concepts that include direct measurement, model analysis, and indirect indicators that can be used across scales; data transmission and analysis systems that avoid costly ship time; quantitative satellite-based sensors; and development of plume dispersion models for direct injection of CO_2. Research activities in support of M&M technologies associated with ocean sequestration have been underway for several years.[6]

For example, for more than 13 years, DOE and the National Oceanic and Atmospheric Administration (NOAA) sponsored the ocean CO_2 survey during the World Ocean Circulation Experiment, monitoring the carbon concentration in the Indian, Pacific, and Atlantic Oceans from oceanographic ships (Box 8-5).

Another research and development effort underway is to develop low-cost, discrete measurement sensors that can be used in conjunction with the conductivity, temperature, depth, and oxygen sensors to measure the ocean profile on oceanographic stations.

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future

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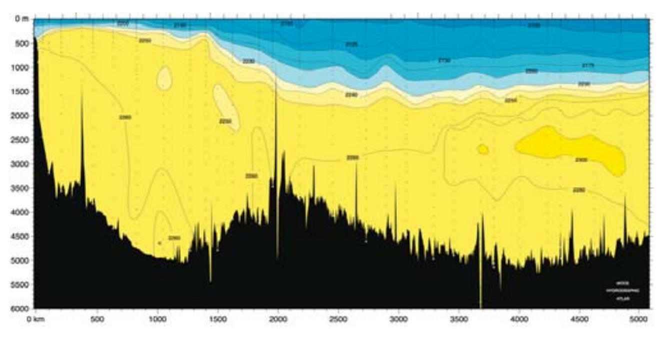
[6] See Section 5.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-55.pdf

BOX 8-5

WORLD OCEAN CIRCULATION EXPERIMENT



Courtesy WOCE Southern Ocean Atlas

The **World Ocean Circulation Experiment (WOCE)** was a component of the World Climate Research Program (WCRP) designed to investigate the ocean's role in decadal climate change. NSF, NASA, NOAA, the Office of Naval Research (ONR), and DOE supported U.S. participation in WOCE. Scientists from more than 30 countries collaborated during the WOCE field program to sample the ocean on a global scale with the aim of describing its large-scale circulation patterns, its effect on gas storage, and how it interacts with the atmosphere. As the data are collected and archived, they are being used to construct improved models of ocean circulation and the combined ocean-atmosphere system that should improve global climate forecasts.

In 2004, as its final activity, the WOCE program published a series of four atlases, concentrating respectively on the hydrograph of the Pacific, Indian, Atlantic, and Southern Oceans. The Southern Ocean is given a separate volume because of the importance of the circumpolar flow on the transport of heat, freshwater, and dissolved components. The volumes each have three main components: full-depth sections, horizontal maps of properties on density surfaces and depth levels, and property-property plots. The vertical sections feature potential temperature, salinity, potential density, neutral density, oxygen, nitrate, phosphate, silicate, CFC-11, 3He, tritium, 14C, 13C, total alkalinity and total carbon dioxide (see image above), against depth along the WOCE Hydrographic Program one-time lines.

research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio, including the following:

- Measurement of injected CO_2, and the tracking and dispersion of the concentrated CO_2 plume.
- Monitoring of the plume or pool to verify the trajectory and lack of contact with the mixed layer.
- Monitoring of the local fauna for adverse effects of enhanced acidity or alkalinity and/or pH changes.

With iron fertilization, it is not well understood whether the excess production stimulated thereby is exported out of the mixed layer, and on what time scale it remains out of contact with the atmosphere. To better understand this, the following R&D investments in measurement technologies would help:

- Measurement of the amount of CO_2 drawn down per unit of fertilization.
- Characterization of the fate and transport of organic carbon exported deeper in the water column and its longevity from using fertilization technologies, including the spatial and temporal CO_2 concentration histories.
- Technologies that can provide accurate monitoring of local CO_2 concentrations and pH. Monitoring of fauna most likely will involve sampling bacterial populations using advanced biological techniques, but may also include macrofauna as appropriate.
- In addition to the specific measurements noted above, it will also be necessary to conduct ocean circulation studies and modeling support selection of injection and fertilization site and estimating storage timescale. As in deep ocean injection, the impact of fertilization on the ocean's biota and chemistry can be monitored carefully to determine the behavior and possible impacts (e.g., pH changes, fish behavior) to deep ocean systems, including the effects of nutrient fluxes on plankton biogeochemistry.

8.4

Other Greenhouse Gases

As discussed in Chapter 7, a wide variety of substances other than CO_2 contribute to the atmospheric burden of GHGs. Other GHGs include methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), perfluorocarbons (PFCs), sulfur hexaflourine (SF_6), hydrofluorocarbons (HFCs), tropospheric ozone precursors, and BC aerosols. These gases are emitted from both point sources (industrial plants) and diffuse sources (open pit coal mines, landfills, rice paddies, and others), and offer unique challenges for M&M of emissions due to their spatial and temporal variations. A robust R&D program should consider direct measurements of emissions and reporting methods that will become part of a larger integrated system. Moreover, the program should consider the needs for M&M both for point sources, and for the extensive and important diffuse sources, such as those associated with agriculture.

Technology Strategy

Advanced technologies can make important contributions to direct and indirect M&M approaches for point and diffused sources of emissions. Realizing the contributions of these technologies is the focus of an R&D portfolio that combines a number of areas, across a number of agencies, including NASA's A-Train (Figure 8-3).

In the near term, technical improvements to measurement equipment and sampling procedures can improve extended period sampling capabilities that would allow better spatial and temporal resolution of emissions estimates. Software development that allows further integration of measurement data with emission modeling processes can lead to improved estimates. In addition, instruments can be developed to measure from stand-off distances (tower measurements), and from airborne and space-borne sensors to address regional, continental, and global reductions of GHG emissions.

In the long term, development of inexpensive CEMs, satellite-based sensors, and improved accounting estimates of emissions offer promise. Integrating modeling techniques, including inverse modeling procedures that integrate bottom-up and top-down emissions data, regional data or global data are also desirable to identify data gaps or confirm source levels. To facilitate the delivery of cost-effective solutions, the strategy will couple academic and national laboratory R&D to benchmarking and transfer to industry for production and deployment.

Current Portfolio

A wide range of R&D programs currently exists in the area of M&M of emissions of other GHGs. The goals of these programs are to develop an integrated system that meshes observations (and estimations) from point sources, diffuse sources, regional sources, and national scales; inexpensive and easily-deployed sensors for a variety of applications, such as stack emissions, N_2O emissions across agricultural systems, CO_2 fluxes across forested regions, CO_2 and other

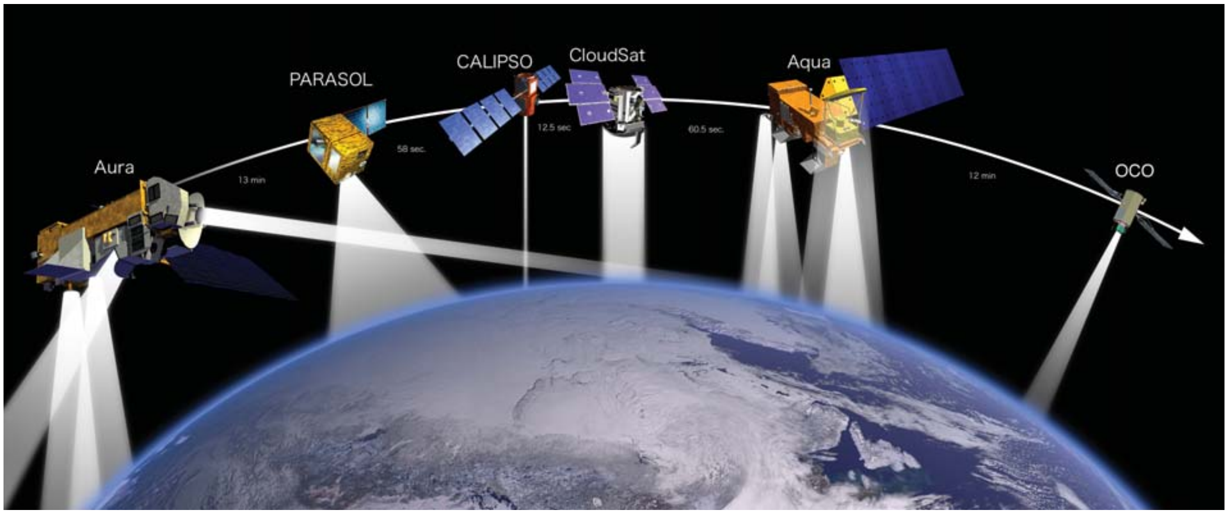


Figure 8-3. NASA's "A-Train" satellite constellation will consist of six satellites flying in formation around the globe. Each satellite will have unique measurement capabilities that greatly complement each other. Near simultaneous measurements of aerosols, clouds, temperature, relative humidity, radiative fluxes, and atmospheric constituents will be obtained over the globe during all seasons.

Courtesy: NASA

GHG emissions from transportation vehicles; accurate rules-of-thumb (reporting/accounting rules) for practices that reduce emissions or increase sinks; a high-resolution system that captures process-level details of sources and sinks (e.g., CO_2 or CO_2 isotopes) and a methodology to scale it up reliably; and data archiving and analysis system-to-integration observations and reporting information.[7]

The following is a summary of some of these programs:

- Annual national inventories prepared by EPA rely on both indirect modeling techniques and direct measurement data. These inventories capture changes in the characteristics and activities related to each source, and are subject to ongoing improvements and verification procedures. The indirect modeling procedures developed for these inventories are particularly important to capture emissions from diffuse area sources where individual measurements are not practical.
- Through the Advanced Global Atmospheric Gases Experiment (AGAGE) Network and other university-led measurement programs, NASA Earth science research includes measuring global distributions and temporal behavior of biogenic and anthropogenic gases important for both stratospheric ozone and climate. These include CFCs, HCFCs, HFCs, halons, N_2O, CH_4, hydrogen, and carbon monoxide. Measurements made at the sites in the NASA-sponsored AGAGE network, along with sites in cooperative international programs, are used in international assessments for updating global ozone-depletion and climate-forcing estimates and in NASA's triennial report to the Congress and the EPA on atmospheric abundances of chlorine and bromine chemicals.
- NOAA monitors the global atmospheric concentration of CH_4, N_2O, CFCs, HFCs, halons and SF_6, in addition to CO_2, through its network of observatories and global cooperative programs. Through these measurements, the global climate forcing by GHGs is updated annually.
- There are generally well-established measurement procedures for energy and industrial point sources, as well as for diffuse sources that are involved with voluntary programs of reduction (e.g., natural gas, coal mines) or are subject to monitoring through regulatory programs for other gases (e.g., landfills). Ongoing integration of these direct measurement results with indirect modeling procedures is part of the national inventory process.
- Recent activities for sources such as agricultural soils, livestock, and manure waste focus on advanced modeling of emissions with verification and validation by direct measurements. Improvements to sampling and measurement techniques are a current priority for these sources.
- A number of measurement technologies have evolved to address the diffuse nature of many of the non-CO_2 sources. These include advanced chamber techniques for *in situ* sensors, FTIR, tracer gas, micrometeorological methods, and leak detection systems. The results of these measurements are being used to verify and feed back to emission factor development.
- BC and tropospheric ozone precursor emissions are an emerging area of importance. Although there is long history of monitoring particulate matter and ozone precursor emissions for criteria pollutant inventories, investigations into the particular sources, speciated forms, and fate of these gases and aerosols that are most applicable to climate forcing potential have become a priority research area.
- EPA is conducting analysis and research to improve GHG inventories and emissions estimation methods, implementing formalized quality control/quality assurance procedures and uncertainty estimation. This concentrated effort will improve all emission estimates for all source categories by identifying areas to target for improved or expanded M&M efforts.
- EPA and the aluminum industry have developed common protocols for the measurement of perfluorocarbon emissions from aluminum primary production facilities to ensure comparable global data.

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

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[7] A detailed review of these R&D activities can be found in Section 5.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-56.pdf

These include:

- Further development of measurement, monitoring, and sampling techniques for agricultural sources, particularly in the area of N_2O from agricultural soils, and CH_4 and N_2O from manure waste. These techniques would address the temporal and spatial variation that is inherent to these emission sources.
- Development of high quality and current emission factors for BC, and, to some extent, tropospheric ozone precursors where there is limited measurement data available.
- CEMs that can measure multiple gases are well developed, but improvements in performance, longevity, autonomy, spatial resolution of measurements, and data transmission would improve measurement of multiple gases. CEMs have particular application to industrial and point sources; however, applying CEM technology to more diffuse sources is also an area for further research.
- Modeling activities that increase the accuracy of spatial and temporal estimates of CH_4 and N_2O from area-type sources such as wetlands, wastewater treatment plants, livestock, and agricultural soils. These are sources that are typically too numerous to measure and monitor on an individual basis, but can be addressed through indirect modeling techniques to account for global, national, and regional emissions. More sophisticated modeling practices could improve the accuracy of the estimates, particularly in terms of greater representation of changing conditions of operation.
- Space-based technologies for long-term monitoring of the global distribution and transport of BC aerosols and other aerosol types (Box 8-6). The NASA Orbiting Carbon Observatory (OCO) will also serve as a proof of concept for the measurements needed to derive surface sources and sinks of other GHGs, including CH_4, on regional scales. This measurement approach will have applications to future spaceborne measurements of GHGs. Planned collaborations with international partners—e.g., the Japan Aerospace Exploration Agency's GOSAT mission—will lead to a more complete suite of global GHG observations.
- Sophisticated modeling procedures that can fingerprint large-scale measurements to unique sources could help integrate continental and global measurements with regional and local emissions data.

BOX 8-6

CONCEPTS FOR GLOBAL CO_2 AND BC MEASUREMENTS

As part of its scientific research mission supporting the Climate Change Science Program, NASA conducts R&D of aerospace science and technology that is relevant to CCTP M&M needs. Several new measurement concepts have been developed by NASA. The Orbiting Carbon Observatory (OCO) concept involves space-based observations of atmospheric carbon dioxide (CO_2) and generates the knowledge needed.

An Aerosol Polarimetery Sensor (APS) for the NASA Glory space mission is being designed to provide improvements in monitoring of BC aerosols compared to the legacy satellite instruments that only measure the intensity of reflected sunlight.

Studies indicate that multi-angle spectro-polarimetric imager (MSPI) and a high spectral resolution LIDAR (HSRL) would have the capacity to provide column average estimates of aerosol optical depth, particle size distribution, single scattering albedo, size-resolved real refractive index, and particle shape to distinguish natural and anthropogenic aerosols and improve projections of future atmospheric CO_2.

- Collaborative research between EPA's National Vehicle and Fuels Emission Laboratory (NVFEL), manufacturers of vehicles/engines, emission control technology, and analytical equipment manufacturers on developing N_2O measurement techniques for emerging gasoline and diesel engines and their emission control systems. Measurement technology applies to both laboratory and field measurement.

Science questions driving future development of technologies for climate change M&M include:

- What effects do anthropogenic activities have on aerosol radiative forcing, at accuracies sufficient to establish climate sensitivity, i.e., < 1 W/m^2?
- What are the separate impacts of anthropogenic and natural processes, including urban activities, fuel-use changes, emission controls, forest fires,

and volcanoes, on trends in particulate pollution near the surface?

- What connections are there between cloud properties and aerosol amount and type?

8.5

Integrated Measurement and Monitoring System Architecture

The integrated system architecture established the context of a systems approach to delivering the information needed to plan, implement, and assess GHG reduction actions (Figure 8-4). This architecture provides a framework for assessing M&M technology developments in the context of their contribution to observation systems that support integrated system solutions for GHG reduction actions and helps in identifying more cost-effective solutions. It enables the benchmarking of planned improvements against current capabilities.

An integrated M&M capability has the ability to integrate across spatial and temporal scales and at many levels, ranging from carbon measurements in soils to emissions from vehicles, from large point sources to diffused area sources, from landfills to geographic regions. This capability is graphically depicted in Figure 8-5. The integrated system builds on existing and planned observing and monitoring technologies of the CCSP and includes new technologies emerging from the CCTP R&D portfolio.

Advanced M&M technologies offer the potential to collect and merge global and regional data from sensors deployed on satellite and aircraft platforms with other data from ground networks, point-source sensors, and other *in situ* configurations. Wireless microsensor networks can be used to gather relevant data and send to compact, high-performance computing central ground stations that merge other data from aircraft and satellite platforms for analysis and decision-making. An integrated system provides the benefits of compatibility, efficiency, and reliability while minimizing the total cost of M&M.

Technology Strategy

The strategy for developing an integrated system is to focus on the most important measurement needs and apply the integrated concept design to ongoing technology opportunities as they arise. The near term focuses on development of observation systems at various scales. The longer term focuses on merging these spatial systems into an integrated approach employing IEOS. IEOS will enable and facilitate sharing, integration, and application of global, regional, and local data from satellites, ocean buoys, weather stations, and other surface and airborne Earth observing instruments (IEOS 2005). Although IEOS serves multiple purposes, one outcome will be the strengthening of U.S. capabilities to measure and monitor GHG emissions and fluxes. Development of software and tools to further

Integrating System Architectural Linking Measurement and Monitoring Observation Systems to Greenhouse Gas Reduction Actions

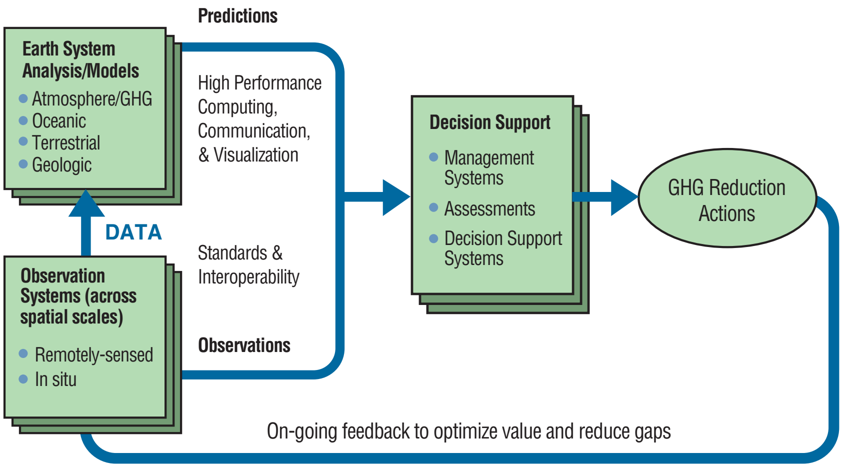
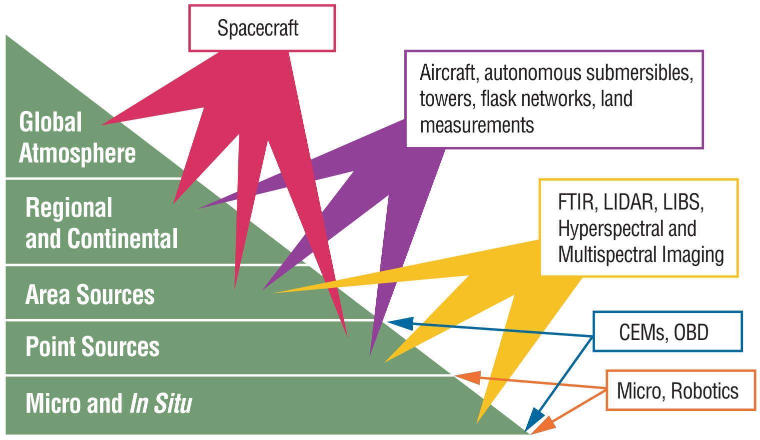


Figure 8-4. Integrating System Architectural Linking Measurement and Monitoring Observation Systems to Greenhouse Gas Reduction Actions

Courtesy NASA

Hierarchical Layers of Spatial Observation Technologies and Capabilities



FTIR:Fourier Infared Spectrometer
LIDAR: Light Detection And Ranging
LIBS: Laser Induced Breakdown Spectoscopy
CEM: Continuous Emmission Monitors
OBD: On-Board Diagnostics Vehicles

Figure 8-5. Hierarchical Layers of Spatial Observation Technologies and Capabilities

Courtesy NASA

integrate measurement data with emission modeling processes will be an ongoing component of the technology strategy.

Current Portfolio

The current Federal R&D portfolio has been targeted at a number of developments, with the goal to develop an integrated system that meshes observations (and estimations) from point sources (e.g., power plant or geologic storage site), diffuse sources (e.g., from commercial and agricultural systems), regional sources (e.g., city/county), and national scales so that checks and balances up and down these scales can be accomplished. The system should be able to attribute emissions/sinks to both national level activities and individual/corporate activities and provide verification for reporting activities. The system must be inexpensive and use easily-deployed sensors for a variety of applications (stack emissions, N_2O emissions across agricultural systems, CO_2 fluxes across forested regions, CO_2 and other GHG emissions from transportation vehicles). In addition, the integrated system should have data archiving and analysis capability for system-to-integration observations and reporting information.[8]

Some examples of the current R&D activities include:

- **Global.** R&D programs enabled by NASA's Earth Observation System research satellites, NOAA's operational weather and climate satellites, and NOAA's distributed ground networks (including the Mauna Loa observatory) support improved understanding and measurements and monitoring capabilities relevant to CCSP and CCTP. The transition of NASA's research to NOAA operational use (referred to as "Research & Operations") enhances program planning and budget execution capabilities for the U.S. Earth Observation System.
- **Continental.** Recent research has tried to determine the net emissions for the North American continent using different approaches: inversion analysis based on CO_2 monitoring equipment as currently arrayed, remote sensing coupled with ecosystem modeling, and compilation of land inventory information. European researchers have embarked on a similar track by combining meteorological transport models with time-dependent emission inventories provided by member states of the European Union.
- **Regional.** Advanced technologies, such as satellites, are being developed to monitor and/or verify a country's anthropogenic and natural emissions. NOAA is building an atmospheric carbon monitoring system under the CCSP using small aircraft and tall communications towers that will be capable of determining emissions and uptake on a 1000-km scale (Box 8-7).
- **Local (micro or individual).** A number of techniques are currently used to directly or indirectly estimate emissions from individual sites and/or source sectors, such as mass-balance techniques, eddy-covariance methods (i.e.,

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[8] For a detailed analysis of the current research, see Section 5.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-51.pdf.

AmeriFlux sites, source identification using isotope signatures), application of emissions factors derived from experimentation, forestry survey methods, and CEMs in the utility sector.

Future Research Directions

The current portfolio supports the main components of the technology development strategy. Within constrained Federal resources, this portfolio addresses the highest priority current investment opportunities. For the future, CCTP remains open to and seeks to consider a full array of promising technology options. From diverse sources, including technical workshops, R&D program reviews, scientific advisory panels, and expert inputs, a number of such ideas have been brought to CCTP's attention.

- **An overarching measurement-and-monitoring system architecture that integrates a diverse set of models and data from local point sources.** The integrated management system would function at multiple scales (local-regional-global) and have the ability to integrate across spatial and temporal scales and from many sources, ranging from carbon measurements in soils to emissions from vehicles, from large point sources to diffused area sources, from landfills to geographic regions. Development would be facilitated via interagency planning and coordination.
- **Data fusion and integration technologies to support integration of information from numerous sources, such as satellite observations, real-time surface indicators, and reported emissions inventories.** Advances are needed in data handling and processing, and development of innovative sensors, platforms, advanced data protocols and mining algorithms, large storage systems (hardware and software), and computational models. Validation of data elements requires coordination with national and international standards-setting bodies to develop protocols for interoperability of datasets.
- **Platforms for all spatial scales and measurement layers, for example, from new types of global sensors on satellite platforms and from new airborne platforms (e.g., remotely operated or autonomous) facilitated by IEOS.** Monitoring of GHG emission sources and geologic sequestration would be supported by portable platforms for sensors and autonomous units that measure, analyze, and report emissions, while ocean sequestration would be supported by autonomous submersible systems with appropriate sensors and reporting capabilities. An integrated system of sensors, indicators and models would be critical to platform development and use, as well as data collection and integration.
- **Capability for remote sensing of GHGs and aerosols from beyond low Earth orbit (geostationary L1).** Features would include multi-spectral spectrometers, "stare" capability with high temporal resolution, spatial resolution on the order of a few kilometers, and ability to measure a variety of constituents.
- **Rapid prototyping and benchmarking of existing integrated system components (sensors, data handling, models, algorithms, decision support) and those evolving through R&D.** Laboratory capability will test and evaluate the efficacy of the solutions to systems integration.
- **Wide area networks (wireless mesh-communications with no towers or satellites**

BOX 8-7

NOAA
REGIONAL CARBON MONITORING

As part of the Climate Change Science Program (CCSP) and the North American Carbon Program (NACP), NOAA is building a Carbon Cycle Atmospheric Observing System mainly across the United States in order to reduce the uncertainty in the North American carbon sink. To measure carbon fluxes on a 1000-km scale over land, vertical profiling is necessary. From about 24 sites, small aircraft will, on a weekly basis, carry automatic flask sampling systems. These systems will collect 12 samples for analysis of carbon gases and isotopic carbon ratios at predetermined altitudes from the surface to about 8 km. In conjunction, tall communications towers (~ 500 m) will sample carbon and other GHGs continuously from about 12 U.S. sites. This technique will be capable of determining regional carbon sources and sinks and may have applications in the Climate Change Technology Program (CCTP) for monitoring the effectiveness of, for example, sequestration activities.

connected sensors) that provide robust communications. These networks would employ low-cost point GHG sensors that collect data at an appropriate frequency and spatial resolution.

- **Decision support tools to incorporate data and information from M&M systems (e.g., change in emissions, regional or continental information, fate of sequestered gases), along with model sensitivities and model predictions generated by CCSP activities into interactive tools for decision makers.** These tools would provide the basis for "what-if" scenario assessments of alternative emission reductions technologies (e.g., sequestration, emission control, differential technology implementation time schedules in key countries of the developing world). There is also a critical need for tools that can measure and monitor or simulate functionality in the design of climate change mitigation technologies.

8.6 Conclusions

Meeting the GHG measuring and monitoring challenge is possible with a thoughtful system design that includes near- and long-term technology advances. Figure 8-6 presents a set of representative M&M technologies that are featured in the technology strategies of this chapter and could arise over time from ongoing and future research investments. The resulting timeline illustrates the technology advances that, if realized, would produce continuing progress in GHG measuring and monitoring systems. Such systems are needed to support the design and implementation of strategies to ensure a future of near-net-zero GHG emissions.

Near-term opportunities for R&D include, but are not limited to (1) incorporating transportation M&M sensors into the onboard diagnostic and control systems of production vehicles; (2) preparing geologic sequestration M&M technologies for deployment with planned demonstration projects; (3) exploiting observations and measurements from current and planned Earth observing systems to measure atmospheric concentrations and profiles of GHGs from planned satellites; (4) undertaking designs and deploying the foundation components for a national, multi-tiered monitoring system with optimized measuring, monitoring, and verification systems; (5) deploying sounding instruments, biological and chemical markers (either isotopic or fluorescence), and ocean sensors on a global basis to monitor changes in ocean chemistry; (6) maintaining *in situ* observing systems to characterize local-scale dynamics of the carbon cycle under changing climatic conditions; and (7) maintaining *in situ* observing systems to monitor the effectiveness and stability of CO_2 sequestration activities.

Through sustained R&D investments in monitoring and measurement capabilities, the United States can (1) enhance its ability to model emissions based on a dynamic combination of human activity patterns, source procedures, energy sources, and chemical processing; (2) develop process-based models that reproduce the atmospheric physical and chemical processes (including transport and transformation pathways) that lead to the observed vertical profiles of GHG concentrations due to surface emissions; (3) determine to what degree natural exchanges with the surface affect the net national emissions of GHGs; (4) develop a combination of space-borne, airborne, and surface-based scanning and remote-sensing technologies to produce 3D, real-time mapping of atmospheric GHG concentrations; (5) develop specific technologies for sensing of global methane "surface" emissions with resolution of 10 km; (6) develop remote-sensing methods to determine spatially resolved vertical GHG profiles, rather than column-averaged profiles; and (7) develop space-borne and airborne monitoring for soil moisture at resolutions suitable for M&M activities.

Technologies for Goal #5: Measure and Monitor Emissions

	NEAR-TERM	MID-TERM	LONG-TERM
Energy Production & Efficiency Technologies	• M&M Specifications and Performance Standards • Low-Cost Sensors and Communications • Samplings, Inventories, & Estimates	• Sensor Networks • Remote Sensing Prototype • Direct Measurement to Replace Proxies and Estimates	• Fully Operational Sensor and Satellite Networks that Feed the Integrated Architecture
Carbon Capture, Storage, & Sequestration	• M&M Specifications and Performance Standards • Low-Cost Sensors and Communications • Samplings, Inventories, & Estimates • Ability to Assess the Integrity of Geologic Reservoirs • Improved Leak Detection from Capture and Pipelines	• Sensor Networks • Remote Sensing Prototype	• Fully Operational Sensor and Satellite Networks that Feed the Integrated Architecture
Other GHGs	• M&M Specifications and Performance Standards • Low-Cost Sensors and Communications • Samplings, Inventories, & Estimates	• Sensor Networks • Remote Sensing Prototype • M&M Techniques for Agricultural Sources	• Fully Operational Sensor and Satellite Networks that Feed the Integrated Architecture
Integrated M&M Systems Architecture	• Identification of Metrics, Criteria, Sources, and Requirements for Measurements • Comprehensive Vision of Integrated Systems Architecture and Technology Needs	• Model and Data Specification • Large Scale, Secure Data Storage System • Data Visualization Tools • M&M Processes Incorporated into Design of Climate Change Technologies	• Fully Operational Integrated MM Systems Architecture (Sensors, Indicators, Data Visualization and Storage, Models)

Figure 8-6. Technologies for Goal #5: Measure and Monitor Emissions
(Note: Technologies shown are representations of larger suites. With some overlap, "near-term" envisions significant technology adoption by 10–20 years from present, "mid-term" in a following period of 20–40 years, and "long-term" in a following period of 40–60 years. See also List of Acronyms and Abbreviations.)

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