except Africa. Sufficient reports of thicker, persistent contrails were received from North America and Europe to enable useful comparisons with satellite imagery and numerical prediction techniques (Figure 1).

The goal for the 2005 event is to obtain many more reports so that information is available to help pinpoint the conditions under which contrails do and do not form in different meteorological and flight regimes around the world.

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—L. H. CHAMBERS, NASA Langley Research Center, Hampton Va.; and D. P. DUDA, National Institute of Aerospace, Hampton, Va.

MEETINGS

Monitoring Carbon From Space

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Over the past two centuries, there have been great changes in the atmospheric concentrations of greenhouse gases including carbon dioxide, methane, and carbon monoxide (CO_2, CH_4, and CO). The natural cycles of these gases have been strongly affected by human actions such as fossil fuel burning, land use change, and fire management.

While there will always be uncertainty in understanding a system as complex as the world's climate, there is strong evidence that global warming is occurring and is being caused by increases in greenhouse gases in the atmosphere. The effects of such warming are already significant, and they are certain to accelerate in future decades as the magnitudes and feedback effects of the causative human actions increase.

Of these gases, CO_2 is the major contributor to anthropogenic climate change. CO_2 levels have increased from 280 parts per million (ppm) in 1750 to over 375 ppm currently. This concentration is higher than at any time in the past million years. Only around half of the extra carbon dioxide human activity sends into the atmosphere stays there; unidentified "sinks" on the land or ocean surface absorb the rest. The rate of climate change would be much greater without this absorption. Further, there is great variability in the strength of sinks from year to year, largely as a response to climate anomalies such as the El Niño–Southern Oscillation (ENSO). To make reliable predictions of future CO_2 concentrations, the sink strength variability needs to be understood since it is also subject to climate change.

Quantifying the variations in space and time of the sources of CO_2 requires precise and continuous monitoring at global scale. Space-based remote sensing is ideally placed to contribute to this monitoring.

More than 60 researchers discussed this topic at the European Space Agency's (ESA) European Space Research Institute (ESRIN) in Italy, during the three-day Carbon From Space workshop.

The meeting, jointly organized by ESA, the International Geosphere-Biosphere Programme (IGBP), the Integrated Global Carbon Observations Theme (IGCO) of the Integrated Global Observing Strategy (IGOS), and the Global Carbon Project (GCP), brought together the science community, the space agencies (ESA, NASA, and the Japan Aerospace Exploration Agency (JAXA)), and the observation coordinating bodies (e.g., IGCO) to discuss the state of the science, share knowledge of each other's activities, and coordinate measurements and modeling activities.

Status and Prospects for Improved Space-Based Observations

Currently, four orbiting space-based systems are capable of measuring CO_2, CH_4, and CO concentrations in the atmosphere. Although none of these systems was optimally designed for making such measurements, useful results are nonetheless being derived from the NOAA's High-Resolution Infrared Sounder (HIRS) (CO_2), ESA's Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) (CH_4, CO_2), NASA's Atmospheric Infrared Sounder (AIRS) (CO, CO_2), and NASA's Measurements of Pollution in the Troposphere (MOPITT) sensor (CO).

This situation will change shortly, as four additional instruments capable of measuring greenhouse gases will soon be launched.

The first two, the French Centre National d'Études Spatiales (CNES)/European Meteorological Satellite Organisation (EUMETSAT) Infrared Atmospheric Sounding Interferometer (IASI) and the NASA/NOAA Cross-track Infrared Sounder (CrIS), are similar to currently orbiting instruments. They will primarily benefit weather forecasting but also can measure greenhouse gas concentrations. Their operational nature guarantees continuity, which is important given the spatial and temporal variability in carbon exchange between land, ocean, and atmosphere.

The other two instruments, NASA's Orbiting Carbon Observatory (OCO) and JAXA's Greenhouse Gases Observing Satellite (GOSAT), are the first purpose-built CO_2 measurement satellite instruments. They use different technological approaches to the same measurement, and their performance will help guide future missions.

The ESRIN meeting represented an opportunity for Europeans to hear about progress on these missions and to discuss plans for data analysis. Additionally, agency representatives discussed potential European involvement in the missions, such as providing data downlink services.

Current and planned missions offer a significant increase in the capability to measure atmospheric CO_2, but they still leave gaps. Thermal infrared instruments (e.g., IASI) are sensitive only to the small variation in CO_2 in the upper troposphere. Passive near-IR instruments (e.g., OCO) see the stronger signals in the lower troposphere but are limited to sunlit surfaces. This means Passive near-IR instruments are prone to diurnal biases and leave parts of the Earth invisible for much of the year because there is either no or not enough sunlight for reliable measurement. Active instruments (e.g., lidar), in which the satellite provides its own light source, overcome these limitations.

The current technical feasibility of launching lidars into space is the subject of independent studies funded by NASA and ESA (E. Browell, NASA; G. Ehret, German Space Agency (DLR); and P. Flamant, Laboratoire Meteorologie Dynamique, Palaiseau, France) with future joint activity a real prospect.

Validation of Measurements

Validation of measurements is vital in any satellite program, especially for a measurement as potentially controversial as CO_2 concentration. Meeting attendees heard about the existing networks of discrete and continuous measurements taken at the Earth's surface or from aircraft. A problem is that these measurements are taken at specific altitudes, while satellite measurements will integrate concentration over some depth in the atmosphere. More comparable measurements are coming from surface-based upward-looking Fourier transform spectrometers (FTS) or lidars.

The joint presentation by C. Miller (NASA Jet Propulsion Laboratory) and G. Inoue (National Institute for Environmental Studies, Japan) showcased the coordination of these validation efforts among space agencies in support of the launches of GOSAT and OCO. However, such efforts require expansion and further collaboration in order to exploit globally coordinated, pre-existing programs such as Fluxnet.

The Determination of Surface Fluxes

The need to understand surface fluxes is the main use for atmospheric concentration data of greenhouse gases. This requires assimilation of carbon gas concentration estimates into atmospheric models. This theme was highlighted in a specific session on advances in data assimilation from satellites as well as from ground-based atmospheric observations and ancillary information on surface fluxes.

For example, F. Chevalier and coworkers (Laboratoire des Science du Climat et de l'Environnement (LSCE), Paris) presented work on the determination of uncertainties in flux estimates for the 22 regions of the Atmospheric Tracer Transport Model Intercomparison Project (TRANSCOM) based on existing ground observations and column-integrated satellite data. This work highlighted the need for improvements in assimilation methods, the development of the models themselves to ensure best use of the data, the need to understand bias and error in satellite observations, and the importance of ancillary data to characterize the surface and the atmosphere.

The Carbon Cycle Data Assimilation Scheme (CCDAS) presented by T. Kaminski (FastOpt) represents an example of the current direction involving the coupling of surface and atmospheric models. In these combined models the unknown quantities are the internal state and critical parameters of the surface models. This combined approach can use not only atmospheric composition data also but the many other observations of surface properties available from remote sensing.

Ancillary Atmosphere and Surface Datasets

Additional information on the atmosphere and the surface is important because satellite sensors only measure radiances and because the signals of trace gas concentration must be disentangled from those of other atmospheric properties and the variability of the surface. Progress is being made in obtaining estimates of the key variables of water vapor content, aerosol concentrations, and aerosol type. However, the presentation by S. Kinne (Max Planck Institute for Meteorology, Hamburg) highlighted the difficulties: even estimates of aerosol concentration from two instruments—the Multiangle Imaging Spectroradiometer (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS)—on the same satellite, exhibit considerable differences.

For water vapor content, R. Lang (Max Planck Institute for Chemistry, Mainz), in presenting a new global water vapor climatology from the Global Ozone Monitoring Experiment (GOME), showed that differences between models and observations remain quite large regionally. While the combination of satellite observations, models, and ground-based measurements is vital to extracting consistent global products, the need for products that are independent of models is equally important to allow identifying bias and error.

Discussions on the current state of surface observations focused on a series of initiatives to generate global products such as land cover, burned area, wetland dynamics, and information on the absorption, by plants, of photosynthetically active radiation. For example, N. Gobron (Joint Research Centre, Ispra, Italy) identified the progressive drying of the Australian continent from the late 1990s by the examination of anomalies in the fraction of absorbed photosynthetically active radiation (f_{APAR}) on land, derived from data recorded by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), something that confirms predictions from models.

A common theme of this session was the need to reconcile results from different projects and satellites to increase the temporal record and provide better sampling, greater continuity, and hence improved confidence.

It is also clear that not all quantities can be best determined from space. In situ observations are vital for modeling, especially when measurements of climate and soil are concerned. In many instances, such observations provide key information to aid the correct interpretation of satellite data. They also contribute data that will never be generated from satellites, such as soil carbon. The planning of space-based observations should therefore aim to reinforce in situ monitoring by strengthening links with regional ground-based experiments by including in situ measurement campaigns for validation purposes.

Toward Integrated Carbon Observations

While advances in individual domains of carbon research will be made, the underlying theme of the meeting was the need for interaction within and among the scientific community, the agencies such as IGCO responsible for coordinating observations and programs, and the space agencies responsible for space-based observations and satellites. A platform for such activity is the organization of a Coordinated Enhanced Observation Period (CEOP), a two-year period of observations of many aspects of the carbon cycle led by the coordinating agencies such as IGCO and the IGOS-P Global Atmospheric Chemistry Observations Theme (IGACO) and the scientific community (GCP) in consultation with the space agencies (NASA, JAXA, ESA). This CEOP, workshop participants indicated, should be organized to coincide with launches in 2008 of the CO_2 satellites OCO and GOSAT in order to make the most effective use of the wealth of data that these satellites will produce.

The Carbon from Space workshop was held in Frascati, Italy, from 6–8 June 2005.

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