GLOBAL CARBON MONITORING

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ABSTRACT:

Recognizing the growing need for improved Earth observations, over 130 governments and leading international organizations are collaborating through the Group on Earth Observations (GEO) to establish a Global Earth Observation System of Systems (GEOSS) by the year 2015. They are contributing their respective Earth monitoring systems to GEOSS and interlinking these systems so that they work together better. They are developing common technical standards to make it possible to pool information, and they are promoting the free sharing and dissemination of Earth observations and data. This expanding coalition of countries and organizations has already transformed the ability of governments to manage natural resources and promote the safety and well-being of their citizens. Recognizing the growing need for improved Earth observations, over 130 governments and leading international organizations are collaborating through the Group on Earth Observations (GEO) to establish a Global Earth Observation System of Systems (GEOSS) by the year 2015. They are contributing their respective Earth monitoring systems to GEOSS and interlinking these systems so that they work together better. They are developing common technical standards to make it possible to pool information, and they are promoting the free sharing and dissemination of Earth observations and data. This expanding coalition of countries and organizations has already transformed the ability of governments to manage natural resources and promote the safety and well-being of their citizens. The GEO through its Members and Participating Organizations, has begun work to implement a global carbon observation and analysis system addressing the three components of the carbon cycle (atmosphere, land and ocean) to provide high-quality information on carbon dioxide and methane concentrations and emission variations. By combining observations, reanalysis and product development we will be able to develop tools for carbon tracking and carbon storage evaluation including improved global networks of atmospheric CO_2 observations, air-surface exchange flux networks as well as surface ocean CO_2 and related marine biochemistry observations.

1. BACKGROUND

1.1 General Instructions

The role of greenhouse gases in global warming processes and as an important element of the global carbon cycle is widely recognised by GEO participants. With the advent of the technical means to provide new monitoring and measurement of GHGs from space in 2009, CEOS has identified the coordination of these measurements and their application as a top priority for the coming years. NASA, NOAA and ESA have agreed to work with JAXA to establish the necessary international framework to facilitate this coordination, aimed at access to the data, its application, and security of future supply.

The task will foster the use of space-based greenhouse gas (GHG) observations and consolidate data requirements for the next-generation GHG monitoring missions from space. The task will create a synergistic strategy for easy access to GHG satellite observations such as GOSA to harmonise the next generation of GHG satellite observations. The task will pursue the technical and organisational progress required for the application and integration of results with those of the other GEO Carbon CL-09-03 tasks, to which it is closely linked CL-09-03a (Integrated Global Carbon Observations (IGCO)) and CL-09-03b (Forest Carbon Tracking). To ensure the necessary coordination and integration of outcomes of these tasks, the task will also serve as a vehicle for the purposes of coordinated reporting to CEOS and GEO. To facilitate this function, and to raise the profile and priority of all 3 Carbon tasks within GEO, the task will establish an international coordination Task Force within the CEOS structure (and reporting to SIT with the other GEO tasks which CEOS leads). This Task Force will work with, and seek to ensure maximum synergies from, the various initiatives within CEOS contributing to the GEO Carbon tasks.

1.2 Overview of Carbon Monitoring

Understanding the global carbon cycle, and predicting its evolution under future climate scenarios is one of the biggest challenges facing science today with huge societal implications. The uncertainty in the natural sinks of the carbon cycle is a leading contributor to the uncertainty in climate predictions due to the feedbacks between climate change and the carbon reservoirs. The spatial and temporal distribution of natural sinks over land and oceans remains elusive, which precludes better quantification of their underlying mechanisms and drivers. In addition to natural sinks, anthropogenic emissions from fossil fuel burning and land use change must be known at regional level and with better accuracy for taking well-informed policy action. A key reason for our lack of understanding of the global carbon cycle is a lack of global observations. An increased, improved and coordinated observing system for observing the carbon cycle is vital.

Completing an Integrated Global Carbon Observing system (IGCO) within the Group on Earth Observation (GEO) and the Global Climate Observing System (GCOS) will involve thousands of scientists, agency representatives, technicians, and policy makers. One key element of an Integrated Global Carbon Observing system is to provide communication points to facilitate the flow of information from the data providers to the data users and to summarize the current state-of-the-art and the way forward.

The concentrations of CO_2 and CH_4 in the atmosphere are higher now than at any time in the past 20 million years. Current levels of CO_2 have increased by nearly 40% from pre-industrial levels of about 280 ppm to more than 386 ppm today, and they continue to rise at about 2 ppm per year. Current levels of CH_4 of over 1800 ppb are two-and-a-half times the pre-industrial value of 700 ppb. After a decade of stability, CH_4 has recently begun rising again. The main causes of the observed increase in CO_2 are fossil fuel combustion and modifications of global vegetation through deforestation, land-use changes and agricultural management. The amount of CO_2 released each year through fossil fuel burning alone, continues to increase exponentially. In 2008, 8.7 Pg C were emitted. An estimated 0.5-2.5 Pg C per year were also emitted from deforestation and land-use change during that year. Emissions rose sharply between 2000 and 2008 reflecting increasing per capita emissions, with emerging economies contributing the largest share of the increase; coal burning was the dominant source of the increased emission Almost half of the total anthropogenic CO_2 emission accumulates in the atmosphere; the rest is absorbed by sinks in the ocean and in terrestrial ecosystems. These natural sinks thus provide a discount of around 50% on the potential greenhouse effect caused by increasing CO_2 emission. The ocean takes up some 2.2 Pg C per year and soils and vegetation 2.7 Pg. The global magnitude of these sinks is uncertain, their patterns in time and space even more so.

Natural CO_2 sink strengths vary with weather and climate. The large global climate perturbations driven by events such as El Niño or volcanic eruptions exert a strong influence on the exchange of CO_2. Regional climate anomalies such as the recent droughts in Amazonia North America and Western Europe (2005, 2002 and 2003 respectively) can turn temporarily the land biosphere carbon sink into a source. Methane is another potent GHG. Its emissions include man-made sources reflecting the use of fossil fuel, waste decomposition in landfills, livestock production and rice cultivation, as well as natural sources such as wetlands, termites and wildfire. After being stable for the past decade, CH_4 concentration started to increase again early in 2007. This pattern is yet unexplained, illustrating our limited understanding of CH_4 sources and sinks processes. Methane sources are sensitive to both socioeconomic drivers and climate variations. The spatial distribution of CH_4 fluxes is highly uncertain. The atmospheric chemistry cycle of CH_4 is quite unlike that of CO_2. Hydroxyl radicals (OH) remove CH_4 from the atmosphere on a time scale of eight years, a process that is also sensitive to climate change, through chemical reactions in the atmosphere. Therefore, a small change in CH_4 sources or in the chemical sink can tip the CH_4 budget out of balance.

1.3 Carbon Cycle Observations

Carbon-cycle science and the underpinning observations must be able to provide robust inferences on the distribution of carbon fluxes and their controlling processes. In part, this knowledge can be based on improving existing or developing observational methodologies, but novel approaches are needed as well. For example, atmospheric increases in CO_2 concentration can be measured directly, terrestrial fluxes due to land-use change can be estimated from stock changes (e.g. forest to non-forest conversions), and terrestrial-atmosphere CO_2 flux measurements can be used to calibrate models to give spatial estimates of annual net carbon exchange. In other cases, satellite observations of indicators of primary production (e.g., ocean color; Fraction Absorbed Photosynthetically Active Radiation, FAPAR) will guide process-based models. Time-series measurements of dissolved inorganic carbon in the deep ocean allow tracking of the ocean sink and surface ocean measurements can aid in evaluating the influence of interannual variability in oceanic fluxes, such as that caused by El Niño events.

2. CORE OBSERVATION ELEMENTS

2.1 Atmospheric Domain

Surface-based in situ, remote sensing and aircraft observations of high precision CO_2 and CH_4 concentrations across a global network of at least 1000 surface stations, covering in particular all tropical and boreal ecosystems as well as vulnerable ocean regions, such as the Southern Ocean. Synoptic global fluxes assessed from satellite observations of column-integrated and vertical distribution of atmospheric CO_2 and CH_4. Sufficient accuracy will be obtained by making auxiliary observations of aerosols and clouds or development of other disturbance free methods. Instrument calibrations will be traceable to a primary standard.Observation of isotopes of CO_2, CH_4 and N_2O, and O_2/N_2 ratio to evaluate land and ocean sink ratio, and the locations of these sinks.

2.2 Terrestial Domain

In situ micrometeorological observations of ecosystem fluxes made by the eddy covariance technique, with observations of CO_2, water vapor and heat fluxes at representative locations, including a range of successional stages and land-use practices and intensities. Over wetlands and rice paddies, eddy covariance CH_4 flux observations should also be made. A global network of about 500 ecosystem flux measurement stations is envisioned.Inventories of the spatial and global distribution of forest and woodland biomass, measured in situ at a minimum of five yearly intervals, and annually by high resolution remote sensing techniques. Key control indices such as nitrogen content, and leaf area index will also be measured Inventories of the spatial and global distribution of litter and soil organic carbon content in the upper meter of soil, measured in situ typically at ten-year intervals, again including nutrient content, and measures of decomposability.In situ and remote-sensing observations of the spatial distribution of permafrost, peatland and wetland organic carbon pools down to bedrock, measured typically at ten-year intervals, but at higher frequency in fast changing areas. Monitoring of the abrupt loss from these pools, due to events such as peatland fire or collapse of permafrost land.Carbon harvested as crops and wood products, as well as peat and biomass harvested and used for energy production.Changes in the carbon content of reservoirs, lakes and freshwater sediment pools.

2.3 Ocean Domain

A global ocean CO_2 exchange (flux) measurement network using a coordinated combination of research vessels, ships of opportunity, and autonomous drifting buoys measuring the surface CO_2 partial pressure difference between atmosphere and seawater. Dissolved carbon content of the ocean with global coverage, measured typically at 10-year intervals, to estimate the input of anthropogenic CO_2 into surface waters.

A coordinated and international effort of pCO_2 observations in coastal oceans, data-banking, data quality check and data synthesis requiring a variety of platforms (research vessels, ships of opportunity, autonomous vessels, moorings, drifters, gliders).

3. SATELLITE MONITORING

Satellite monitoring is indespensable for understanding of whole scale levels of carbon flux.

3.1 Atmospheric Domain

Satellite data are key to improving the spatial coverage of the sparse in-situ networks, particularly where there are large gaps in coverage. A re-analysis of the infrared bands from the NOAA AIRS instruments has produced estimates of mid-troposphere column integral CO_2. But as these observations are weighted to the upper troposphere they cannot be used to constrain surface fluxes.

The SCIAMACHY instrument on the European environmental satellite (ENVISAT, launched in 2002) is the first to provide CO_2 and CH_4 measurements sensitive to all altitude levels, including the atmospheric boundary layer. This capability comes from its nadir observations in the near-infrared/shortwave-infrared spectral range. The accuracy for CO_2 is a few parts per million with around 1% relative accuracy for CH_4. The observed CO_2 horizontal gradients agree well with those derived from assimilation modeling based on in situ station data. SCIAMACHY data are already being used for initial inverse modeling of CH_4 fluxes.

The GOSAT was launched in short succession in early 2009. It has a goals of measuring CO_2 and CH_4 column integrals at better than 1% accuracy. This accuracy would be sufficient to improve the surface flux estimates compared with that obtained from using the surface in situ network alone. While GOSAT attained orbit and has begun sending data, the OCO launch failed. However, OCO 2 is now being planned and the experience gained through the construction, testing and calibration of the original will be useful in designing the second version. In addition EUMETSAT and ESA are planning to include solar absorption channels for the detection of CH_4 and potentially CO_2 in the Sentinel 5 UVNS sensor that will be flown on the European post-METOP system from 2020 onwards.

Data and retrieval algorithms from GOSAT are currently being tested and early retrievals look promising. Improvements to the treatment of the aerosol and/or cloud disturbances are in progress, including the retrieval of surface pressure from an O_2 absorption band. Further data integration activities are required to take full advantage of this new data product, i.e. validation with surface based total column observations from the TCCON network and comparison with data measured from aircraft.

In the longer term data from active (LIDAR) sensors could improve upon the passive sensor capability used so far, and might be able to provide better spatial and temporal coverage.

3.2 Ocean Domain

The ocean domain has seen a dramatic increase in the quality and quantity of observations coming from hydrographic cruises, ships of opportunity and moored buoys in the last decade. The International Ocean Carbon Coordination Project (IOCCP, http://ioc3.unesco.org/ioccp/Index.html) has been leading the coordination of the ocean observations and produces regular updates of maps of the observing system. Actions following workshops on hydrography, surface CO_2 partial pressure (pCO_2) and O_2 observations continue to improve the ocean observing system.

The surface data from all of these platforms have been combined into large data products. Previous global climatologies, e.g. Takahashi et al. (2009), gave a spatially detailed but time-averaged view of fluxes. But in a major synthesis effort, the Surface Ocean CO_2 Atlas (SOCAT) project, these are now in the process of evolving towards more time-resolved data products, which reveal decadal and shorter trends. Recent efforts have shown that, for regions such as the northern hemisphere oceans, which are well covered by shipping routes, it is possible to constrain the net annual uptake flux to an accuracy of order 20%, with good seasonal and spatial resolution. The Carbo-Ocean project for the North Atlantic achieved this by combining data from a surface observing network with remotely sensed observations and re-analysis products.

New observations of O_2 from Argo free-drifting buoys (http://www.argo.ucsd.edu/) have shown promising results and an increase in the number of buoys carrying O_2 sensors is expected as the technology improves in reliability and power consumption.

3.3 Terrestial Domain

In situ observations of terrestrial fluxes and reservoirs are a major challenge owing to the heterogeneous nature of the land surface, and the difficulties in modeling the behavior of biological processes. The Fluxnet project is a collaboration of regional flux networks, intended to combine data from the regions for global synthesis. There has been a large expansion in the number of eddy covariance towers from around 100 in 2000 to almost 600 in 2009. The network has expanded to every continent. The main Fluxnet regional networks are: Ameriflux, Asiaflux, CarboEurope, CarboAfrica, LBA (Amazonia), OzFlux (Oceania). In terms of temperature and rainfall, the range of climates covered is almost complete; cold and dry climates, and wet and warm climates are exceptions. Fluxnet provides an important data set covering many different ecosystem types, climates and disturbance classes. Most of the measured variables are crucially relevant to the carbon cycle: fluxes of carbon, water and energy; meteorological data; ancillary data at each sites (e.g. LAI, biomass, soil carbon, soil moisture, etc.). Data availability has improved dramatically with the release of the Fluxnet Synthesis Data product in 2006, when a global scale synthesis activity was started (http://www.fluxdata.org). This synthesis requires the standardization of all data from different regional networks.

4. REMOTE SENSING OF LAND AND OCEAN SURFACES

Remote sensing of land-surface characteristics has proven extremely valuable, for example the long time-series of AVHRR-derived NDVI since the 1980s, and the higher resolution optical (infrared and visible) products from MODIS, Landsat and SPOT. New derived products such as the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) are also derived from remote sensing data. FAPAR is an important parameter in general models (e.g. light-use efficiency models) that estimate terrestrial carbon fluxes over a range of temporal and spatial resolutions. Spatially explicit descriptions of FAPAR, one of the GCOS Essential Climate Variables, since they inform about the relative strength and location of terrestrial carbon pools and fluxes

PAR is monitored as part of the standard protocol at ecological research sites (e.g. Fluxnet). In the AmeriFlux network, sensors are calibrated to Quality Assurance laboratory standards, but few other sites generate reliable measurements of FAPAR that can be meaningfully used for the validation of satellite products. Community efforts are underway to document the accuracy of available space-derived data sets; while ground-based networks, coordinated by CEOS Working Group on Calibration and Validation (CEOS-WGCV), perform measurements relevant to these validation exercises.

Space agencies and other institutional providers generate global maps of leaf area index (LAI) at various spatial resolutions for daily to monthly periods, using mainly optical spaceborne sensors. In this case, the values depend on allometric relationships developed from ground measurements or modeled values simulated global vegetation classes, such as the 12 or so pro posed by the IGBP. Global estimates LAI are generally made at 1 km resolution, which, when compared to local observations tend not to be very accurate for local vegetation types. Several efforts to derive more accurate LAI estimates from remote sensing data are underway. These are most commonly based on empirical relationships derived from ground-based measurements, for instance at validation sites spanning a range of land cover types. Such validation initiatives are now performed in the framework of ground-based networks, including both national research groups and international entities, such as the Land Product Validation (LPV) Subgroup of the CEOS-WGCV. Current validation efforts concentrate mainly on expanding the number of validation sites, and on improving the reliability and accuracy of the ground-based estimates by defining state of the art protocols addressing the very different spatial dimensions of in situ and remote sensing measurements. For active fire mapping the ESA World Fire Atlas provides the longest available continuous global record of active fires, while MODIS is the best currently polar orbiting sensor for this phenomenon. Other polar orbiting (AVHRR, TRMM) and geostationary satellites (e.g. MSG and GOES) extend these observations to better characterize the diurnal cycle of active fire. The WFA has recently been upgraded using a new nighttime algorithm and extended back to 1991. For fire radiative energy, SEVIRI and MODIS are the only currently operating sensors with demonstrated capability to make measurements to the required specifications.

The Global Fire Emission Database (GFED) is an integrated product, combining MODIS, ATSR, and VIRS satellite products of fire activity with the CASA terrestrial biosphere model to estimate CO_2, CO, CH_4 and a suite of other trace gases and particulates from 1997 to the present. The spatial and temporal pattern of fires is relatively well understood but uncertainties in global fire emission estimates remain substantial. Other products exist as well (FLAMBE, GLOBCARB).

Satellite observation from space using Synthetic Aperture Radar (SAR) are also beginning to provide ‘all-weather’ land-surface information, in particular over cloud-affected regions in the tropics and high-latitudes, where optical satellite data are sparse. JAXA developed a systematic acquisition strategy for the ALOS L-band Synthetic Aperture Radar (PALSAR) for generation of global coverage of wall-to-wall SAR data for tracking land-use change. ALOS PALSAR builds on the JERS-1 L-band SAR technology and acquisition strategy (used for tropical and boreal forest monitoring during its lifetime), and should provide the first systematic global observations for generating forest-change and derived biomass maps. Several research programs are underway to implement the use of SAR, as well as airborne/spaceborne LIDAR, to derive robust global estimates of vegetation aboveground biomass. Satellite missions such as “BIOMASS” (ESA) is being specifically designed for this purpose.

5. FUTURE REQUIREMENTS FOR REMOTE SENSING

The current carbon observation systems only provide a very good picture of the trends and distributions of carbon cycle gases in the global atmosphere as a whole. They also provide the current framework for understanding carbon fluxes among the atmosphere, ocean, and terrestrial biosphere. These observation systems are diverse and loosely coordinated, but have to some extent served the purpose of informing decision-making over the past few decades. However, the driving science and policy questions for the 21st century require a globally coherent observation system-of-systems that can provide relevant regional-scale information, can be traceable to primary standards, and is interoperable with other Earth Observation systems. To achieve these goals requires augmenting the observation and analysis systems in all domains. The fundamental observational gaps are related to the impacts of climate change on the carbon cycle, and to verifying and reporting reliably on land use and fossil fuel emission management strategies. The system should be able to inform policy at regional, national, and international levels and should be consistent in space and time, with sufficient accuracy to detect regional trends within the variability of each sub-region.

5.1 Atmospheric Domain

Satellite and other remote sensing observations will be needed to create an effective carbon observing system. Future satellite observations have a critical need for parallel long-term aircraft and surface-based remote sensing observations to first establish the bias in the spatial and temporal patterns observed from satellites, and then to correct them. Satellites are currently our only means to obtain global coverage, but improvements in accuracy are needed. With the advent of the technical means to provide new monitoring and measurement of GHG from space, CEOS has identified the coordination and application of these measurements as a top priority for the coming years. To foster the use of space–based CO_2 and CH_4 observations and consolidate data requirements for the next–generation GHG monitoring missions from space, a strategy for easy access to GHG satellite observations should be developed. A coordinated planning effort towards the next generation of a constellation of GHG satellite observations is also required. Space-based high-precision (1 ppm or so) measurements of the column-integrated CO_2 molecular density with frequent global coverage are highly valuable in determining terrestrial and oceanic CO_2 fluxes provided they are linked to a reference scale. By linking the spatial distributions of CO_2 with atmospheric flux inversions, data assimilation techniques, and coupled atmospheric, terrestrial and ocean carbon modeling, the scientific community will be able to de termine sources and sinks of CO_2 at unprecedented space and time resolution. In addition, this measurement stream will have value in its independence from in-situ measurements or “bottom-up” model-derived estimates of CO_2 flux. The atmospheric inversion approach exploits the atmospheric gradients in CO_2, which are strongest in the lower part of the atmosphere. The flux retrieval accuracy is a function of the precision and sample density of measured total column CO_2. The measurements of the total column integrated CO_2 molecular density down to the Earth’s surface need to be at 0.3% (1 ppm) precision or better for significant improvements in our knowledge of sources and sinks. Existing instruments such as AIRS/AMSU, IASI/AMSU and CrIS are able to monitor CO_2 and other trace gases from space. They have high spectral resolution, which allows isolation of a large set of specifically sensitive CO_2-channels from the interfering water vapor and temperature signals from the free troposphere and above, but exclude the lower troposphere. Currently, a precision of about 0.5% at a space-time scale of 100 km/weekly is achieved for the middle-tropospheric CO_2 column abundances. However these characteristics do not allow for the inversion of surface sources and sinks. Using the short-wave infrared signal, as done by SCIAMACHY, OCO 2 and GOSAT, has the advantage of penetrating the atmosphere down to the ground. The SCIAMACHY sensor has been flying since 2002 on ESA's ENVISAT mission and has been successful in producing CH_4, CO and the first CO_2 column integrated retrievals over land, with an accuracy for CO_2 of a few ppm and for CH_4 around 1% relative accuracy. This accuracy is sufficient to improve quantification of regional-scale methane surface fluxes. The Orbiting Carbon Observatory (OCO - NASA) was designed to use measurements of reflected sunlight in the short-wave infrared to provide global, high-precision measurements of the column-integrated CO_2 mixing ratio with a precision of 0.3% (1 ppm). The observatory carried three high-resolution spectrometers, one for O_2 (0.765 µm) and two for CO_2 (1.6 and 2.06 µm). OCO was expected to serve as a pathfinder for future long-term CO_2 monitoring missions, but unfortunately OCO failed to achieve orbit. A follow-on mission is now being planned. The Greenhouse Gases Observing Satellite (GOSAT) is the world's first purpose built satellite to observe the concentration of CO_2 and CH_4, from space. The main purpose of the GOSAT project is to produce more accurate estimates of the flux of GHG on a subcontinental basis (several 100 km resolution). A GOSAT follow-on mission study is now underway, and it is essential that this should take into consideration the needs of the GEO Carbon tasks

To fulfill the GCOS requirements on the GHG ECV's CO_2 and CH_4 the next generation of GHG satellite measurements needs to provide high accuracy measurements with high spatial resolution (1-2 km) and good global coverage (global coverage at the equator with 1-3 day repeat-frequency to get good monthly mean GHG fields), the latter to effectively monitor emissions from strong local source areas for example industrialized urban areas or power plants. In the long term this could be achieved by an international GHG-satellite constellation equipped with both passive sensors (for GHG imaging and monitoring the natural and anthropogenic hot spots) and active sensors (to deliver very precise but spatially sparse GHG data). The active sensor mission could be accomplished using the measurement technique based upon Laser Absorption Spectroscopy (LAS), which is a powerful tool for high-precision trace gas spectroscopy. LAS provides measurements of CO_2 via measurements of received power at wavelengths on and off an absorption line. LAS and DIAL, operating in a pulsed mode, which is not required for column measurement, have been proposed as the next generation GHG instru ments. ASCENDS, A-SCOPE, and other LIDAR instruments have been studied by ESA, NASA, JAXA and several other agencies, but it has to be recognized that high technology barriers still have to be crossed in order to achieve such a mission.

The passive-sensor mission needs to be developed as soon as possible to continue the SCIAMACHY and GOSAT GHG time series on CO_2 and CH_4 and needs to include the lessons learned from the SCIAMACHY, OCO and GOSAT projects. There is currently a high risk that after around 2014/15 there will be no space-based GHG sensor with sensitivity down to the surface in place. Thus, the highest short term priority for the international community is to continue the time series of space-based planetary boundary-layer CO_2 and CH_4 measurements which was started with SCIAMACHY on ENVISAT (launched in 2002, expected mission end 2013) and is continued by GOSAT (launched in 2009, expected mission end 2014). These measurements should be continued over the next decades with incrementally improved passive sensors, ideally in a GHG-satellite constellation within the international system of operational meteorological satellites. Within this overall priority, over the next 5 years, the first priority is the continuation of SCIAMACHY and GOSAT, and the development of improved passive GHG observation capabilities from space.

5.2 Global Data Integration

The task of carbon data integration has several objectives: spatial integration in which measurements from different regional programs are coherently combined; completeness in which we try to ensure that all important processes of the carbon cycle are observed; temporal integration, to be able to use long-time series for improved model prediction, as well as evaluation of impacts associated with climate policy decisions; process integration in which data are combined to form a single, consistent view of the carbon cycle with consistency between inferences from atmospheric, oceanic, terrestrial and socioeconomic data. Previous sections of this document have dealt with the first three objectives and here we focus on the fourth. Although this may not appear to be related to the observing system, it is obvious that any coherent observing strategy must take account of how observations will be used.

The process of integrating multiple streams of observations into carbon cycle models requires assimilation techniques that modify model behavior to match observations. This approach is given a wide variety of names such as model-data fusion, the multiple constraint approach or carbon-cycle data assimilation. Such techniques were initially applied long ago to the tuning of the seasonal cycle of atmospheric CO_2 concentration but it was around 2000 that the use of formal data assimilation methods allowed rapid development in the field. Examples of such applications are the estimation of phenology parameters from satellite observations, estimates of photosynthetic parameters using CO_2 and heat fluxes, a larger suite of parameters in a terrestrial model and biomass inventory data. Oceanic applications are rarer, but several notable applications exist. For example, atmospheric data assimilation techniques (e.g. 4DVAR) were used in the atmospheric inverse models to establish the atmosphere-ocean fluxes of CO_2 and CH_4. Applications can be divided into two broad categories: those that constrain the internal state of the model by assimilating state variables; those that estimate poorly known internal parameters of the model. Clearly state variable assimilation will produce a closer fit to observations and so is preferred where the best possible performance within the observing period is required (i.e. diagnostic applications), while assimilation to estimate parameters is intended to improve the underlying behavior of the model and targets prognostic applications.

Most importantly, every observation must be associated with an uncertainty since this is necessary to weight the observation's influence on the model. Beyond this, use of any observation in a data assimilation system requires an operator that can map the internal state of the model onto the observed variable. Here there are practical choices to be made if the published data are themselves the result of a complex model such as a radiative retrieval. In general it is best to bring these observation operators into the data assimilation process itself since otherwise the error statistics of the observation are really those of the observation operator. This can be difficult to represent. As an example, uncertainties in calibration can generate coherent errors that will not be captured by pointwise descriptions of error. Experience with numerical weather prediction suggests that the generation of observational operators requires close collaboration between the modeler and the expert in the particular observed variable. As a scientific task, the generation of these observation operators is as equally important as the generation of data sets of observations using them.

6. CONCLUSIONS & ACKNOWLEGEMENTS

GEO Carbon Strategy report is a document describes current status of global carbon monitoring, and also future expectations of synergetic approach to achieve the goal. Followings are the contributers of this document, and author would like to express hertfelt appreciation and congratulations to all.

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