Carbon theme in GMES

HALO
discussion paper

Draft

Tuesday, 02 November 2004

Johannes Flemming
Tony Hollingsworth
Pedro Viterbo

Content

Summary

Within GMES, the integrated projects MERSEA (ocean theme), Geoland (land & vegetation theme) and GEMS (atmosphere theme) as well as the GMES service element PROMOTE deal directly with elements of the global carbon cycle.

The recently published IGOS-P Carbon Theme report is a peer-reviewed statement of requirements needed to monitor the carbon cycle. It proposes an interacting and mutually constrained system of ocean, land and atmospheric carbon models assimilating EO-data of atmospheric CO_2 and vegetation status as well as in-situ observations of atmospheric and maritime CO_2. The carbon related activities of the GMES IP's could be combined to establish an operational implementation of the proposed system.

GEMS subproject on Greenhouse gases will operationally provide monthly atmospheric CO_2 fields from satellite based infra-red sounders (AIRS and IASI) by assimilation in ECMWFs forecast model and by independent retrieval. The envisaged spatial resolution is 7 - 15° in a tropospheric column for tropics and mid-latitudes. Further, GEMS will provide and attribute CO_2 fluxes from the derived atmospheric CO_2 fields and in-situ observations by means of inverse modelling.

Geoland's subproject Observatory Natural Carbon implements a land-vegetation model in ECMWFs forecast system which provides monthly carbon fluxes and stocks of the terrestrial biosphere in a 1° spatial resolution after 2006. EO-observations of the vegetation status (LAI) and precipitation data will be assimilated in the model.

MERSEA models will provide maritime carbon fluxes and stocks without operational commitment till 2008 because the quality of the ecosystem components has not been sufficiently validated yet. MERSEA's global ocean model (Mercator) and the basin scale models will include biogeochemical modules capable of assimilating ocean colour data as indicator of maritime biological activity. The retrieval of ocean colour data from satellites belongs to the MERSEA activities.

GEMS CO_2 assimilating model and Geolands Carbon - land - vegetation model will be implement in ECMWFs forecast system, which will ensure their sustainable operation. Geolands and possibly MERSEAs fluxes could be used in GEMS atmospheric model. On the other hand, GEMS flux estimates from inverse modelling can be constrained or validated by the CO_2 fluxes from Geoland (and MERSEA) if produced in a stand-alone mode

Assuming that the ONC land-surface model and assimilation modules are adopted by GEMS, and that GEMS makes a successful transition to operational status towards the end of 2008, then we can look forward to an operational implementation of the Atmosphere and Land parts of the IGCO carbon Plan. If MERSEA's ecological models will be successfully validated they may contribute the missing maritime part.

The GMES contributions focus on modelling and assimilation and on the retrieval of carbon information from satellites. GMES has no commitment to foster in-situ observations relevant to the carbon cycle.

1 Introduction

The paper provides an overview on envisaged activities in GMES[1] relevant to monitoring and modelling of the global carbon cycle. As part of the HALO[2] work, the different contributions will be presented to evoke a discussion about their joint transition to a more unified GMES contribution. Problems to be discussed are the thematic analysis of common interfaces and the technical coordination of a timely product exchange.

GMESs main building blocks are integrated projects (IP) dedicated to the thematic priorities of ocean, land & vegetation, atmosphere, water resources, natural risks and security. The following IPs will provide information about the current status of the carbon cycle:

- GEMS (atmosphere theme, trace gases and aerosol)
- Geoland (land and vegetation theme)
- MERSEA (ocean theme)

The GMES's IPs are accomplished by ESA founded Earthwatch GMES service elements (GSE) with the aim to provide satellite based data to the IP. The GSEs are currently in the consolidation phase. Many GSEs target on vegetation, forest and algal bloom in a regional or continental scale but have mostly no direct commitment in the carbon problem. GSE with services related to the carbon cycle are:

- PROMOTE (GSE for the atmosphere theme)
- Forest Monitoring

Carbon is stored and exchanged within the ocean, atmosphere and land biosphere components of the earth system. The recently published IGOS_P [3] Carbon Theme report is a peer-reviewed statement of observation and assimilation requirements needed to document routinely the evolution of the carbon cycle and to improve our understanding of it. The report can be used as guideline to evaluate the different contributions in GMES and to improve the links between them. The commitment of the individual IPs to the carbon cycle issue is, however, of different scope in terms of the scientific focus and the maturity the operational service.

A joint GMES carbon system would help a) to better understand the carbon cycle and its current perturbation, and b) to meet EU commitments for verifiable monitoring of carbon emissions (e.g., Kyoto protocol).

The dynamics of the biological production, both in ocean and land, atmospheric CO_2 exchange and the quality of relevant EO-retrievals is strongly controlled by meteorological conditions. Therefore, beside the actual carbon data exchange, the

[1] GMES is a joint initiative of the European Commission and the European Space Agency, designed to establish a European capacity for the provision and use of operational information for Global Monitoring of Environment and Security.

[2] HALO is a GMES specific support action (SSA), which will be responsible for the Harmonization of Atmosphere, Land and Ocean GMES backbone. The objective of HALO is to enable an efficient and coherent data exchange between the relevant IP's of GMES. HALO will provide agreed recommendations for the data architecture of GMES in its operational phase starting in 2008.

[3] Integrated Global Observing System Partnership

common use of meteorological and EO-data would be further link between the GMES IPs.

The report starts with a clarification of technical terms such data assimilation, inverse modelling, neural networks and Bayesian interference. The next chapter explains the structure of the proposed IGOS carbon modelling and assimilation system. Finally, the carbon related contribution of GEMS, Geoland and MERSEA as well as of the GSEs Promote Forest Monitoring will be presented. A more detailed discussion is dedicated to the interaction between GEMS Greenhouse Gas subproject and Geoland's Observatory Natural Carbon.

2 Clarification of technical terms

Bayesian Interference is probabilistic concept which includes the uncertainty (error bars) of parameters in the inference process. Bayesian concepts can be used to explain the techniques of data assimilation and inverse modelling: Observation with an estimated uncertainty and prior knowledge (model equation) are combined to find posterior information including its uncertainty about the atmospheric fields (data assimilation) or fluxes (inverse modelling).

Data assimilation provides an optimal estimation of the state of the earth system (e.g. atmospheric CO_2 fields) by combining the often sparse or indirect (satellite) observation data with model information. The numerical model presents our knowledge about the geophysical processes. Data assimilation helps to better exploit information given by the observation due to merging them with prior information. The numerical implementation of the optimisation in data assimilation can be based on Kalman Filtering or 4D-VAR techniques using an adjoint model.

Neural networks are used to explore (learn) and finally reproduce complex relationships between variables sets (output and input) without knowledge of the geophysical process. They are a computationally cheap tool to partly substitute complex geophysical models or data assimilation schemes. They can be used for the retrieval (inversion) of satellite data (radiation) to a geophysical quantity of interest (CO_2).

Inverse modelling is wide range of numerical techniques, which aims to infer geophysical quantities from sparse or indirect observations. Inverse modelling of CO_2- fluxes (sources or sinks of atmospheric CO_2 concentration) infers the spatial and temporal patterns of the fluxes from a set of atmospheric CO_2 observations by means of a model, which simulates concentration data from given fluxes in its forward mode. The observation could be either in situ measurements or remote sensing data. Since the number of observation is to often to small, which means that many different flux patterns could lead to the same concentration patterns, constrains to the flux estimations have to be made in order to reduce ambiguity: 1. The fluxes are only average values over large areas (North America, Europe) in the greens functions approach. 2. The variational approach, which is connected to 4dVAR data assimilation, can handle high resolution fluxes and large observation set from direct and indirect methods. It is computationally more expensive and requires a first guess of the fluxes and their uncertainty and the coding of an adjoint model.

3 IGOS-P Carbon Theme report

The recently published IGOS-P Carbon Theme report (referred to below as the IGCO report) is a peer-reviewed statement of observation and assimilation requirements needed to document routinely the evolution of the carbon cycle and to improve our understanding of the carbon cycle. The report may be downloaded from the web-site

http://ioc.unesco.org/igospartners/theme.htm

The IGCO report describes inter alia the observational and data assimilation resources needed to provide the best possible estimates of atmosphere-ocean, atmosphere-land, and land-ocean exchanges of CO_2 on a regular basis. The IGCO plan calls for data assimilation activity to determine the atmospheric, ocean and land state vectors, and the fluxes of carbon between these domains. The buildings blocks of the proposed global system (see Figure 1) are:

- Atmospheric transport model
- Ocean carbon model
- Terrestrial carbon model

Each model assimilates respective in-situ and remote sensing data of the carbon cycle elements and its driving process. Only remote sensing is capable to provide global coverage since in-situ observation networks are often sparsely distributed. Besides the observations, inventories of anthropogenic CO_2 emissions and land cover in relation to soil carbon stocks are needed for the model simulations.

Direct observation of carbon is possible for atmospheric CO_2 by the new generation of IR sounders and in situ observations (flask). Resolved maritime CO_2 (pCO_2) can be measured directly mainly at the ocean surface by pCO_2 instruments onboard ships but it cannot be inferred from remote sensing.

Carbon exchange and stocks in the terrestrial and maritime biosphere can be indirectly observed from space by means of spectral vegetation properties (vegetation indices and ocean colour) and land use (burnt surface).

Remote sensing and in situ observation of the atmospheric state (temperature, wind, stability etc.) ocean conditions (SST, SS, surface winds and waves) and earth surface characteristics (burnt area) are vital for simulating the carbon cycle, especially the carbon fluxes between the components of the earth system.

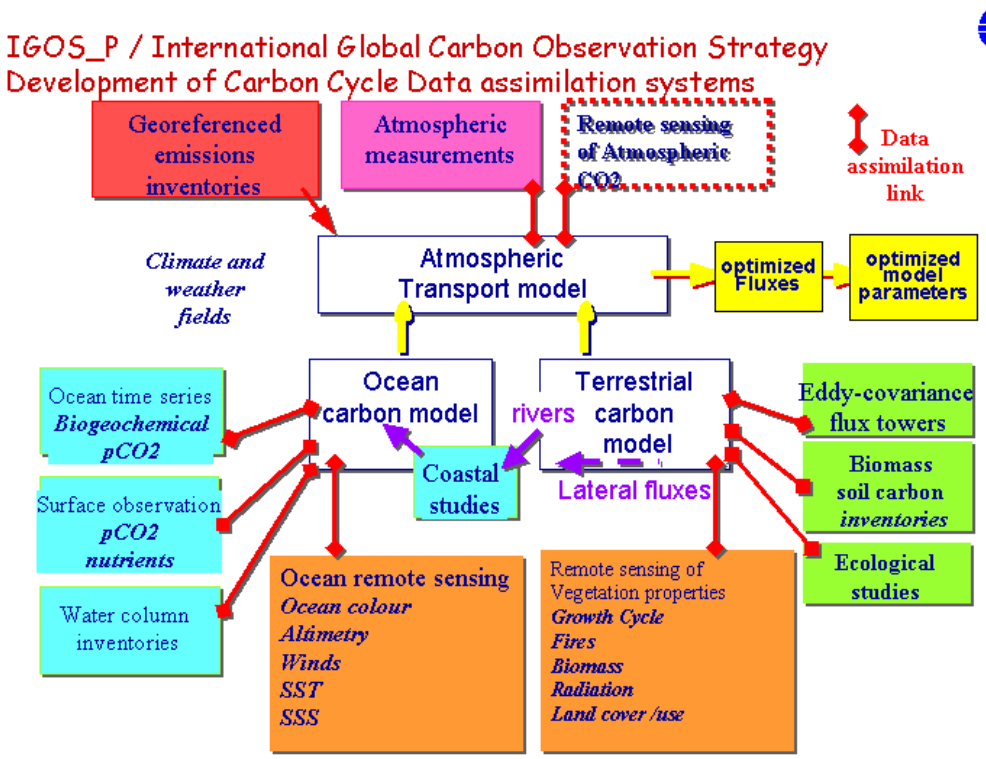

Figure 1 Schematic of Carbon Cycle data assimilation system proposed by IGOS-P

4 GEMS - Green House Gas sub-project

The GEMS (Global and regional Earth-system Monitoring using Satellite and in-situ data) project consists of thematic sub-projects on Greenhouse Gases (GHG), Global Reactive Gases, Global Aerosol and Regional Air quality as well as of sub-projects on a production system and validation effort.

The GEMS GHG project consist of the following carbon-related work packages:

- GHG_1: CO_2 estimates from satellite instruments using 4D-Var data assimilation.
- GHG_2: Stand alone CO_2 estimates from AIRS and IASI instruments
- GHG_3: Independent assessment of CO_2 concentrations and fluxes.
- GHG_4: Estimates of CO_2 sources and sinks using existing atmospheric inversion models.
- GHG_5: Development and testing of an off-line transport model based on IFS.
- GHG_6: Attribution of the inferred CO_2 sources and sinks to causes.

Figure 2 is shows again the structure of the IGCO carbon system, annotated by specific GEMS work package activities (GHG 1 to 6) and by the ONC activity of GEOLAND (see chapter below).

The main focus of the GHG_1 and GHG_2 work packages is the use of data from the new generation of atmospheric sounders (AIRS and IASI) to estimate atmospheric distributions of CO_2 using an advanced meteorological 4D-Var assimilation system (GHG_1) and in 'stand-alone' mode (GHG_2).

The retrieved tropospheric CO_2 products will have a time resolution of 2 weeks to 1 month, and a spatial resolution of 15° (basis) or better (15 days, 7.5°, tentative) for the tropical zone 20N-20S (basis) and the mid latitude zone (tentative, depending on the accuracy obtained).

The function of GHG_3 is to use independent in-situ data to check-out and validate the results of both GHG_1 and GHG_2.

The function of GHG_4 is to use the outputs of GHG_1 & 2 to estimate the spatial distribution of sources and sinks using existing inversion models, with a typical time resolution of a month or longer (see Figure 3). Methodologies will be developed in GHG_5 to improve the inversion methods of GHG_4 (i) by using an inversion model much closer in formulation to the assimilating model in GHG_1 and (ii) by using the full temporal resolution of the CO_2 fields from GHG_1.

The aim of GHG_6 is to apply (i) the variational methodology being developed in the FP_5 CAMELS project and (ii) a new neural-net methodology to infer sources and sinks of CO_2 from the surface flux results of GHG_1 & 2 and to attribute changes in sources and sinks to climate change, and changes in nitrogen deposition, changes in CO_2 and changes in land-use.

The attribution will be done by estimating the changes of parameter values needed in three different terrestrial ecosystem models (TEMs) to fit the atmospheric fields calculated in GHG_4 & 5. Two terrestrial ecosystem models [MOSES (UK

MetOffice), BETHY (MPI-BGC, Jena)] are already being used for variational carbon cycle data assimilation as part of the CAMELS FP5 project. The third TEM will be the improved ISBA-AGS / TESSEL model being developed within the GEOLAND FP6 project, and which is a likely candidate for implementation at ECMWF post 2006 as part of a GMES ONC service.

The CO_2 flux estimates will be used to nudge the internal parameters of these TEMs using 2 distinct approaches: (i) variational data assimilation using the linear adjoint of the TEM ; (ii) a neural network "fit" to the inverse TEM relationship between fluxes and parameters. The first approach will build on the development of a "carbon cycle data assimilation" within the CAMELs project. The second approach is an innovative alternative to formal variational data assimilation.

In the GEMS work up to the end of year 2, the specification of the atmosphere- land surface fluxes of CO_2 in the assimilating model will use a simple climatology of natural and anthropogenic fluxes. If the ONC developments to be discussed below succeed in providing a land surface model and assimilation system that clearly improves on climatology, then it may be used in years 3 & 4 of GEMS, in work-package GHG_1.

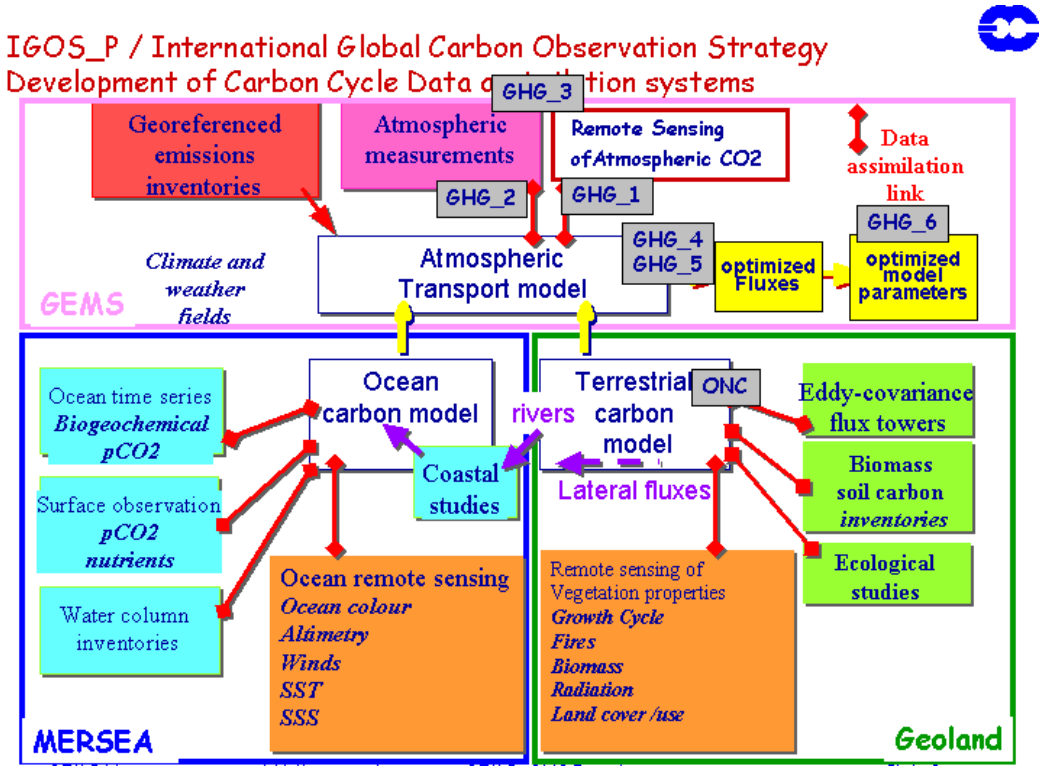

Figure 2 Schematic of Carbon Cycle data assimilation system proposed by IGOS-P annotated by specific GEMS work package activities (GHG 1 to 6) and by the ONC activity of GEOLAND.

5 GEOLAND Observatory for Natural Carbon (ONC)

The main objective of the carbon observatory is to deliver an improved scientific understanding of terrestrial carbon fluxes, in support of the implementation of the Kyoto protocol. More specifically, the building a global full carbon accounting modelling system is envisioned, treating the impact of weather and climate variability on ecosystem fluxes and carbon stocks. The product of the system will be a near real-time analysis of biospheric CO_2 fluxes, globally at 1° resolution, released every 3 or 6 months. The other products of the service will consist of water and energy fluxes, biomass and soil moisture estimates that are fully compatible with CO2 exchange.

The GEOLAND Observatory for Natural Carbon (ONC) is focussed on modelling and assimilation of atmosphere-biosphere-land processes related to the uptake and emission of natural carbon and water vapour.

ONC Modelling: The ONC modelling activity includes an implementation in the ECMWF land surface model (TESSEL) of the detailed carbon-based ISBA_AGS physical treatment of the atmosphere-biosphere treatment interactions. The main modelling focus of ONC is to model the conductance of the vegetation canopy in its interaction with the radiation fields for the fractional absorption of photo-synthetically active radiation (FAPAR), and for the physical processes involved in interception of rainfall and in evapo-transpiration.

ONC Assimilation: The main assimilation focus of ONC is the simultaneous estimation of soil water (through the assimilation of microwave data on soil moisture) and green biomass [through the assimilation of retrievals of Leaf- Area index (LAI) and / or FAPAR (Fractionally absorbed photosynthetically active radiation), obtained from visible and near-infra-red data].

6 Interaction between GEMS GHG and Geoland ONC

The ONC carbon and water fluxes are the products of short-range forecasts with the ONC model starting from the ONC assimilation and driven by observed (where available) or modelled radiation and precipitation fluxes. The ONC estimates will probably have more detailed spatial and temporal scales than those from GEMS_GHG_4. However the ONC fluxes will have used a much cruder representation of the atmospheric carbon distribution than the GHG_4 fluxes.

There is no overlap with GEMS in the model development area. Should the ONC deliver a successfully improved model by its end-date of 2006, then that improved model will be available for use in the years 3 & 4 of GEMS.

The ONC modelling and assimilation tasks will not be addressed by GEMS. The GEMS effort to obtain CO_2 fluxes from atmospheric CO_2 concentration by inverse modelling (GHG_4 & 5) can be described as a top - down approach. In contrast, ONC applies a bottom-up approach, which means modelling fluxes by a model (TEM) describing the vegetation dynamics.

However, if ONC delivers successful modelling and / or assimilation developments by its end-date of 2006, the algorithms and software will be immediately usable by GEMS for years 3 and 4 of the GEMS project.

The GEMS and ONC activities address quite different areas of the overall IGCO plan for documenting and understanding the carbon cycle. GEMS is focussed on atmospheric modelling and assimilation issues, and initially uses a very simple surface formulation for surface carbon fluxes; ONC is focussed on modelling and assimilation for energy, water and carbon issues at the surface. GEMS assimilation work will focus on the advanced sounders AIRS (Aqua) & IASI (MetOp), and on the OCO instrument when it becomes available (launch 2007). ONC assimilation will focus on issues related to the energy exchanges (radiative, latent heat, sensible heat exchanges) between the atmosphere, the vegetation canopy and the land surface. ONC's main assimilation focus will be on the use of Microwave active and passive sensing of soil moisture, and on the use of LAI and/or FAPAR retrievals.

There is no duplication of effort between the two projects. GEOLAND_ONC continues until the end of 2006. GEMS continues until end of 2008. If the ONC modelling, assimilation and data deliverables are successful, then several benefits will be available for GEMS:

- The ONC land surface model could be directly incorporated in the forecast model of GHG_1
- The ONC land assimilation module could be directly incorporated in the assimilating system of GHG_1.
- If however, the ONC assimilation system continues to be run in stand-alone mode (i.e. as it is run in the ONC project) it could provide an additional source of information for GHG_4, as illustrated in Figure 3
- The ONC land-surface module will be used in the attribution studies of GHG_6, using both the variational approach and the neural-net approach to parameter estimation.

Assuming that the ONC land-surface model and assimilation modules are adopted by GEMS, and that GEMS makes a successful transition to operational status towards the end of 2008, then we can look forward to an operational implementation of the Atmosphere and Land parts of the IGCO carbon Plan.

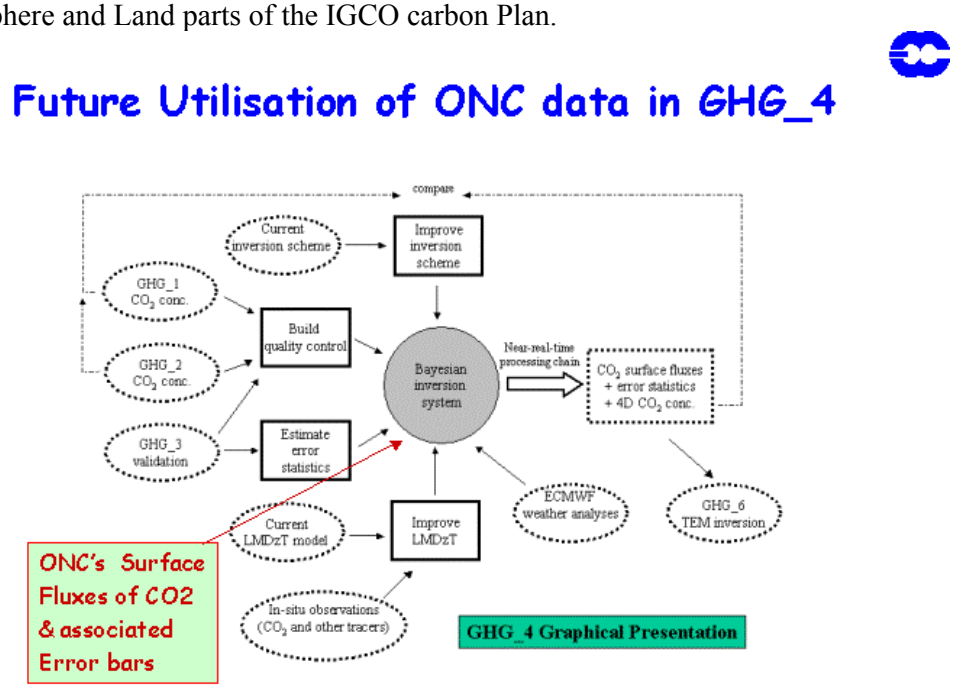

Figure 3 Graphical representation of GEMS GHG subproject and future utilisation of CO_2 fluxes from Geolands ONC.

7 MERSEA contribution

MERSEAs activities related to the carbon cycle are in the following research areas:

- Further development of ecological models and assimilation schemes
- Retrieval of ocean colour from remote sensing
- Validation of ecological models with in situ biogeochemical observations (including CO_2) provided by other projects (CARBOOCEAN)

Research efforts related to the carbon cycle concentrate on the ecological models pursuing two lines of research: (i) global or basin scale bio-geochemical modelling, using simplified models with few compartments aiming mostly at carbon cycle monitoring, and (ii) ecosystem modelling in the coastal seas. The latter is motivated by socio-economic needs, and the existence of local monitoring systems.

MERSEA has no operational commitment towards the ocean carbon cycle before 2008 because the quality of the biogeochemical modules has not been sufficiently validated. The biogeochemical models will include both the biological and the solubility pump for dissolved inorganic carbon and air-sea gas exchange.

The core models in MERSEA with global or basin wide coverage will implement biogeochemical modules in the coming years[4]:

(a) the TOPAZ system already runs an ecosystem component routinely on a weekly basis and plans to assimilate ocean colour data from Oct 2005

(b) the Mercator system plans to run an ecosystem component in delayed mode from Oct 2005 and on a weekly basis with assimilation of ocean colour data from April 2007

(c) the MFSTEP (Mediterranean) system plan to run an ecosystem component on a daily basis in demonstration mode from April 2007

(d) the NE Atlantic system for MERSEA operated by the Met Office is not committed to running an ecosystem component until April 2008[5].

MERSEA starts to develop near real time global ocean colour products from SeaWiFS Meris or Modis - Instruments. MERSEA work package 2 will be providing ocean colour products from October 2006. In combination with the operational physical model, their assimilation in the emerging ecosystem model will give a more realistic description of the standing stocks of surface chlorophyll and phytoplankton biomass.

Atmospheric aerosol fields provided by GEMS subproject on aerosol could be valuable data about iron intake, which controls biological production in the oceans. More detailed river input data is needed by MERSEA ecological models as well.

[4] Information provided by Mike Bell, UK met-office

[5] However, at the Met Office the ERSEM ecosystem model coupled to the POLCOMS system for the NW European shelf has been spun-up near to real-time and will probably be maintained near to real-time. Most of the work in the MetOffice on ecosystem models will be done in collaboration with the NERC CASIX and QUEST projects. (e.g. assimilation of ocean colour data into an NPZD model containing total alkalinity (TALK) and dissolved inorganic carbon (DIC) components coupled to FOAM is being developed in collaboration with the CASIX project).

8 GMES Service elements

PROMOTE

PROMOTE (PROtocol MOniToring for the GMES Service Element on Atmospheric Composition) proposes GMES services relevant to the ozone layer, UV-exposure on the ground, air pollution and climate change.

The services will be implemented in incremental fashion. During the GMES consolidation phase (2004 - 2005) basic services on ozone and surface UV will be implemented as an operational service. Services on air pollution will reach the demonstration phase, while climate services will remain in the development phase.

During the GMES consolidation phase (2004-2005) the PROMOTE services will be defined and implemented. The climate change service will be based on results produced within PROMOTE related EU projects Evergreen (EnVisat for Environmental Regulation of GREENhouse gases http://www.knmi.nl/evergreen/). Evergreen consists of the following building blocks:

Task 1: Retrieval and validation

Trace gas concentrations measured by SCIAMACHY and MIPAS will be retrieved and validated. Advanced radiation transport models and retrieval techniques will allow higher precision and accuracy compared with standard ENVISAT data products. This is necessary in order to meet the EVERGREEN objectives. Extensive validation with independent in-situ, and ground-based and satellite (MOPITT) remote sensing data will establish precision and accuracy figures.

Task 2: Radiation budget modelling

EVERGREEN data will serve as input to atmospheric radiation transfer modelling. The use of measured trace gas distributions, rather than emissions, is expected to produce more accurate radiative forcing calculations. Interpretation of model sensitivities will be given in relation to the Kyoto Protocol.

Task 3: Inverse modelling

Source and sink magnitudes will be established from inverse modelling using the measured trace gas distribution data as a model constraint. Data will be assimilated in a meteorology transport model. The focus will be on CH4 and CO and on regional and seasonal variations. The feasibility of the method will be assessed. End-users involved are a major coal industry and government organisations responsible for Kyoto Protocol issues. Limitations and requirements for a space-borne Global Climate Observing System for top-down emission inventory assessments will be established.

GSE Forest Monitoring

The GSE-FM service combines EO-derived data with in-situ information derived from a sample-based forest inventory, which can be used for greenhouse gas reporting. The main elements of greenhouse gas reporting include national summary statistics of forest area, forest area changes within a land use change matrix, totals and changes in stem volumes, biomass and carbon. The information provided is supplemented by an uncertainty analysis that quantifies the level of error and thereby allows a reliable estimate.

9 Links to carbon related projects

GMES:

- GMES general information: http://www.gmes.info/
- GMES and ESA http://earth.esa.int/gmes/
- Geoland project http://www.gmes-geoland.info
- MERSEA project http://www.mersea.eu.org/
- GEMS project http://www.ecmwf.int/research/EU_projects/GEMS/
- HALO specific support action http://www.ecmwf.int/research/EU_projects/GEMS/
- GSE FM Forest Monitoring http://gafweb.gaf.de/gse/index.htm
- GSE PROMOTE http://www.knmi.nl/promote/

FP 5 and FP 6 projects:

- CARBOOCEAN (FP 6): http://www.pangaea.de/Projects/Carbo-Ocean/
- CarboEurope: (FP 5) A cluster of projects to understand and quantify the carbon balance of Europe http://www.bgc-jena.mpg.de/public/carboeur/
- CAMELS (FP 5) Carbon Assimilation and Modelling of the European Land Surfaces camels.metoffice.com
- EVERGREEN (FP 5) - EnVisat for Environmental Regulation of GREENhouse gases http://www.knmi.nl/evergreen/
- COCO (FP 5) http://www.bgc-jena.mpg.de/bgc-systems/projects/Coco/

International bodies and programmes:

- IGOS - ICOS Integrated Carbon observing system http://ioc.unesco.org/igospartners/Carbon.htm
- Terrestrial Carbon Observations http://www.fao.org/gtos/TCO.html
- Global Carbon Project (GCP) http://www.globalcarbonproject.org/
- FLUXNET - Integrating Worldwide CO_2 Flux Measurement http://daac.ornl.gov/FLUXNET/
- GLOBALVIEW-CO_2 Cooperative Atmospheric Data Integration Project http://www.cmdl.noaa.gov/ccgg/globalview/CO_2/index.html
- SOLAS (Surface Ocean - Lower Atmosphere Study) http://www.uea.ac.uk/env/solas/welcome.html
- International Ocean Colour coordinating group http://www.ioccg.org/index.html