ESA-GCP-CEOS
3rd CARBON FROM SPACE WORKSHOP

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Table of Contents

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List of Abbreviations

3D	Three Dimensional
AGB	Above Ground Biomass
AR5	The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change
ARGO	The broad-scale global array of temperature/salinity profiling floats
BESD	The Bremen Optimal Estimation DOAS (BESD) algorithm
BIOMASS	ESA's Biomass satellite (ESA's seventh Earth Explorer mission)
C_{ant}	Anthropogenic Carbon
CarbonSat	Satellite for the Carbon Cycle (candidate ESA Earth Explorer mission)
CCDAS	Carbon Cycle Data Assimilation System
CCI	European Space Agency Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CERN	Chinese Ecosystem Research Network
CFC	Chlorofluorocarbon
CH_4	Methane
CMIP5	The fifth phase of the Coupled Model Intercomparison Project (CMIP5)
CO	Carbon monoxide
CO_2	Carbon dioxide
COP-21	The 2015 Conference of the Parties of the United Nations Framework Convention on Climate Change
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
DEMs	Digital Elevation Models
DMS	Dimethyl Sulphide
DOAS	Differential Optical Absorption Spectroscopy
EC	European Commission
EE7	Earth Explorer 7
ENSO	El Nino Southern Oscillation
ENVISAT	ENvironmental Satellite
EO	Earth Observation
EPA	US Environmental Protection Agency
ESA	European Space Agency
ESM	Earth Science Mission
ESSP	Earth System Science Programme
EU	European Union
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
fCO2	Fugacity of Carbon Dioxide
FFDAS	Fossil Fuel Data Assimilation System
FLEX	Fluorescence Explorer (ESA's eighth Earth Explorer mission)
GAW	Global Atmosphere Watch
GCOS	Global Climate Observing System

GCP	Global Carbon Project
GEDI	Global Ecosystem Dynamics Investigation Lidar (NASA Mission)
GEO	Geosynchronous Earth Orbit
GHC-CCI	Greenhouse Gas Climate Change Initiative
GHG	Greenhouse Gas
GLAS	Geoscience Laser Altimeter System
GLODAP	Global Ocean Data Analysis Project
GLWD	Global Lakes and Wetlands Database
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GOME	Global Ozone Monitoring Experiment
GOSAT	Green-house gases Observing Satellite
GPP	Gross Primary Productivity
GtC yr-1	Gigatonnes of Carbon per Year
H2S	Hydrogen Sulphide
IAV	Inter-Annual Variability
ICESAT	Ice, Cloud and land Elevation Satellite
ICOS	Integrated Carbon Observing System
IG3IS	Integrated Global Greenhouse Gas Information System
IGBP	International Geosphere - Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LANDSAT	Land Remote-Sensing Satellite
LEO	Low Earth Orbit
LES	Large-Eddy Simulation
LIDAR	LIght Detection And Ranging instrument
LST	Land Surface Temperature
LUC	Land-Use Change
MERLIN	Methane Remote Sensing Lidar Mission
MICROCARB	Microsatellite to map sources and sinks of carbon dioxide (CNES Mission planned for 2020)
MODIS	Moderate Resolution Imaging Spectroradiometer (EOS)
NASA	National Aeronautics and Space Administration
NEE	Net Ecosystem Exchange
NEON	National Ecological Observatory Network
NH	Northern Hemisphere
NOx	Mono-nitrogen Oxides
NPP	National Polar-orbiting Operational Environmental Satellite System Preparatory Project
OCO-2	Orbiting Carbon Observatory – 2
OCO-3	Orbiting Carbon Observatory – 3
OCS	Carbonyl Sulphide
OSSE	Observational System Simulation Experiment
PACE	Pre-Aerosol, Clouds, and ocean Ecosystem (NASA Mission)
PCN	Permafrost Carbon Network

pCO2	Partial pressure of CO2
Pg	Petagrams
PgC	Petagrams of Carbon
pH	Power of Hydrogen
ppb	Parts per Billion
ppm	Parts Per Million
QA	Quality Assurance
RECCAP	REgional Carbon Cycle Assessment and Processes
REDD+	Reducing Emissions from Deforestation and Degradation
S3	Sentinel-3
SAR	Synthetic Aperture Radar
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SEARCH	Study of Environmental Arctic Change research project
SIF	Sustainable Innovation Forum
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SOCAT	Surface Ocean CO2 Atlas
SOCCOM	Southern Ocean Carbon and Climate Observations and Modelling
SOCOM	Surface Ocean pCO2 Mapping Intercomparison
SWAMPS	Severe Wind And Moisture Problems
TANSO	Thermal And Near infrared Sensor for carbon Observations (GOSAT instrument)
TCCON	Total Carbon Column Observing Network
TERN	Terrestrial Ecosystem Research Network
Tg	Teragrams
TLS	Terrestrial Laser Scanning
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WFMD	Weighting function modified differential optical absorption spectroscopy (DOAS) algorithm
WMO	World Meteorological Organization
XCH_4	Column-averaged of CH4
XCO_2	Column-averaged of CO2
yr	Year

Meeting abstracts book and presentations

A link to all meeting presentations and abstract book can be found here:

http://www.carbonfromspace.info

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1. Objective of this document

This document aims to collect and elaborate the major discussion points gathered during the 3rd Carbon from Space workshop that took place in the University of Exeter, UK, the 26th – 28th January 2016.

The meeting, with a participation of more than 80 experts, was aimed at reviewing and discussing the existing scientific knowledge gaps and research priorities areas for the carbon cycle with an emphasis on evaluating where Earth Observations (EO) may contribute over the next decade. The meeting and discussion was predicated on three key elements:

1. Implementation of recommendations of the CEOS Strategy for Carbon Observations from Space.
2. The development of the GEO Carbon project, GEO Greenhouse Gas Initiative and the other coordination projects related to carbon cycle (e.g., IG3IS, the North American Carbon Programme).
3. The review and refocusing of the Global Carbon Project on its move from ESSP and IGBP to Future Earth.

The outcome of the meeting and its conclusions are intended to contribute to guiding scientific activities on carbon cycle research across all domains and their interfaces and to developing better interactions between EO, in situ and model communities in the context of the carbon cycle.

This document, together with additional inputs, will contribute to establish a strong carbon cycle science component in the upcoming programmatic elements of the European Space Agency (ESA) in the 2017-2021 timeframe.

The current document elaborates on the meeting discussions as well as on the different information exchanges with participants and other experts during and after the meeting. The meeting did not cover all areas of research and science in the context of carbon cycle research (e.g., black carbon, disturbances), and as such this document only provides a partial outlook, addressing some of the main EO contributions to carbon cycle science priorities.

The meeting and this document focus mainly on scientific aspects and research needs addressing the ocean, land and atmosphere components, and their interfaces, taking into account the views of EO experts, Earth system scientists, modellers and in-situ observation scientists.

The needs for the services and operational aspects were not discussed in detail at the meeting and are therefore mentioned in this document when pertinent but are not described at length.

2. Introduction

The global carbon cycle involves different biochemical and physical processes and exchanges between the land, atmosphere and ocean components of the Earth system. It involves fast and large fluxes between the different reservoirs in the atmosphere, the oceans and on land, as well as slow processes involving carbon storage in rocks and sediments, chemical weathering, erosion and sediment formation on the sea floor. Human activities such as fossil fuel extraction and burning or land use play a key role in perturbing this complex natural system.

Current levels of atmospheric concentration of CO_2 and CH_4 exceed any level measured for at least the past 800,000 years, with anthropogenic emissions from fossil fuel burning and land use change impacts being the dominant causes of such an increase in the Industrial Era (IPCC, 2013). This increase (e.g., atmospheric CO2 increased by 43% from 1750 to 2014) has accelerated in the last decade with a current average rate of 2.0 $\pm$0.1 ppm yr^{-1} (IPCC, 2013). Also CH_4, after almost one decade of stable atmospheric levels, shows a renewed concentration growth since 2007 that may be related to wetland emissions, agriculture, waste and others (IPCC, 2013)

In this context, understanding the role of natural and anthropogenic contributions to the carbon cycle and its impact on the dynamics of the Earth system is critical for meeting the challenge posed by climate change. This requires quantifying the effect of human activities on the carbon cycle, determining the response of natural systems to these disturbances, projecting future behaviour of carbon pools and fluxes and exploring pathways to atmospheric stabilisation through the management of carbon-climate-human systems.

The Global Carbon Project published a research portfolio in 2010 (Canadell et al., 2010) which, although published 6 years ago, is still relevant in terms of priorities and thematic areas for research in this decade with the ultimate target of deploying a global carbon monitoring system. The main elements of this research agenda are articulated through a number of questions organized in three main areas:

- Diagnostics of the carbon cycle:
    - What is the evolution of the global anthropogenic CO_2 budget?
    - What is the evolution of the global CH_4 budget?
    - What are the regional contributions to the global carbon balance?
    - Enhancing observations and analyses in a globally coordinated way.

- Vulnerabilities of the carbon cycle
    - How big and vulnerable are the Earth's carbon reservoirs?
    - Are there irreversible carbon thresholds?
    - What is the magnitude of the carbon–climate feedback?
    - What are emerging human–carbon interactions of most significance?
    - What is the role of biodiversity for the resilience of carbon pools and sinks?

- Low carbon pathways
    - What is the global mitigation potential of land-based options?
    - How climate protective are land-based mitigation options?
    - What are the carbon cycle consequences of geoengineering the climate system?
    - How much urban mitigation can contribute to emission reductions?
    - What are the requirements to achieve atmospheric CO2 stabilization and how to share the mitigation efforts?

To answer these questions six priority areas were identified in 2010:

1. Optimal deployment of a Global Carbon Monitoring System.
2. Delivery of routine updates of global and regional carbon budgets and attribution of variability and trends to underlying drivers.
3. Assessment of the magnitude of the carbon–climate feedback.
4. Exploration of pathways to climate stabilization and uncertainties.
5. Establishing global synthesis efforts.
6. Communicating the science and policy alignment.

Since the research agenda was published progress has been made in all these priority areas through the GEO and associated research projects leading to the GEO Carbon Strategy and proposed GEO Carbon project, GHG Flagship, through RECCAP and the annual Global Carbon Budget, the projections based on Representative Concentration Pathways in IPCC, the Global Carbon Atlas, ICOS and the ICOS Carbon Portal, the WMO IG3IS and through the North American Carbon programme and others.

Following on from and as a response to the GEO Carbon Strategy (Ciais et al. 2010, 2014) CEOS evaluated the role of Earth observation in providing derived information to complement carbon cycle calculations based on in-situ observations and models. The resulting CEOS Carbon Strategy (CEOS, 2014) provides a framework for the contribution of satellite-based observations and tools to support the carbon science community within this global carbon observing system. In this context, the CEOS report summarises the main actions to be undertaken by space agencies as:

- Ensure the continuity of satellites and established time series data records for carbon-related measurements of land surface properties, ocean colour and related physical properties, coastal and inland water properties, and atmospheric column measurements of carbon dioxide and methane.
- Develop and deploy new missions to acquire high priority measurements for carbon science and policy, including new observations to estimate aboveground biomass and its carbon content, geostationary observations of carbon-containing constituents in coastal ocean waters, improved resolution ocean salinity measurements, and measurements of atmospheric carbon dioxide and methane from complementary Low Earth Orbit (active and passive) and geostationary (passive) satellite constellations.
- Improve satellite data products, including establishment of standard formats and protocols, enhanced validation, securing access to essential *in situ* data, merging of

data from multiple sensors and platforms into enhanced products, and rigorous inter-comparison of data products.

- Produce new data products from existing missions, including maps of wetlands, inundated areas and small water bodies, ocean colour products for inland water bodies, ocean carbon pool products, river discharge and sediments, and anthropogenic emissions of carbon.
- Improve the accessibility and utility of the satellite data and carbon data products derived from them, including transparency in data processing procedures, complete documentation, long-term archives, and provision of products in forms of use to scientists and policy makers.
- Continue and enhance calibration and validation activities, including expanded quality assessments, cross-calibrating additional sensors (e.g., for carbon dioxide and methane), securing access to essential *in situ* validation data, expanding the number of land variables to be validated, and establishing an ocean product validation subgroup.
- Improve institutional arrangements, communications, and joint activities with the carbon community and organizations with carbon interests.
- Improve or establish CEOS Mechanisms to implement the recommendations of the report or to engage in the future planning activities called for in it in a coordinated fashion.

The 3rd Carbon from Space Workshop (University of Exeter, January 2016) was convened as part of the response to calls within the CEOS (see Action Items 16, 20, 27, 35-37) and GEO documents for discussion and exchange of viewpoints within the carbon cycle community across all domains and their interfaces and between the in situ, satellite and model communities.

The workshop was based on dedicated topical sessions with keynote presentations, discussion and breakout groups to define the recommended actions for the atmosphere, ocean and land domains and the interfaces between them.

- Scene setting
- Current understanding of the carbon cycle – pools and fluxes
- Climate, humans and carbon cycle change
- Key problem areas and new frontiers
- Advancing towards an integrated approach

While the talks in these sessions were designed to give broad viewpoints on particular aspects of the carbon cycle with the speakers encouraged to be thought provoking, the breakout discussions were designed to elicit further exchange by crosscutting the topical sessions with the emphasis on producing recommendations to the community, GCP and CEOS.

This document summarises the main sessions, the discussion in the breakouts and attempts to derive a series of recommendations designed to help identify activities on the carbon cycle for Space Agencies over the period 2016-2021 in support of the above GCP and CEOS priority areas.

3. Scene setting

The background to this meeting is a landscape where organisations such as GCOS, CEOS (and its individual agencies), EU and GEO are at various stages of responding, with similar objectives, to the challenges laid down and issues raised by the UNFCCC COP21 and in the IPCC AR5. In addition, changes have taken place in the International Research Programme context with the formation of Future Earth, which impacts on carbon cycle research priorities through GCP. To address these challenges requires an observing and interpretation system that enables improved:

- Monitoring of anthropogenic emissions
- Attribution of past and present changes in land and ocean carbon sinks.
- Projection of future changes in the carbon cycle.

The development of such a system has to contend with the existing situation where there is a need, even in the scientific community, to improve communication, between those who observe the carbon cycle both in situ and from space and those who model it for prognostic reasons. A sub-optimal observing and interpretation system currently exists with shortcomings in both models and observations as well as needs and requirements for the future, specifically:

- In-situ measurements are too sparse and infrequent, yet represent the longest and most detailed records.
- Much of the Earth is inaccessible in terms of measurements
- Some critical variables remain inadequately measured from both satellites and in-situ networks.
- EO signals need extensive processing to extract relevant variables, or the development of adequate observation operators for their assimilation into interpretation systems, and while spatially comprehensive are of short time duration in carbon cycle terms.
- Different models give different answers yet structurally they are similar.
- These model issues apply to all domains and different model scales.
- Models are not comprehensive with some key processes not adequately included by some models (fire, insects, permafrost carbon, methane emissions from wetlands, nutrients interaction, lateral transport,...).
- The interfaces between domains are not specified well because the models were originally designed for domain specific reasons.
- There is an increasing need to further enhance model capabilities to do near-term projections.
- There is increasing pressure to provide answers to specific policy questions (what is the impact of changing land use scenarios e.g.

forest vs. plantation, what is the right balance between implementing climate measures and ensuring food security.

The objectives of the meeting were therefore oriented towards bringing together these nominally disparate elements to initiate exchange and potential coordination between these organisations and the carbon cycle science community such that individual actions can be taken in the appropriate context.

4. Understanding of carbon cycle – pools

Budgets

The Global Carbon Project (GCP) publishes the results of the global carbon budget assessment annually (see Le Quéré et al., (2015) for 2015). The 2015 assessment concluded that for the year 2014 alone, CO2 emissions from fossil fuels and industry grew to 9.8±0.5 GtC yr-1, 0.6% above 2013, continuing the growth trend in these emissions. The emission from land-use change, mainly deforestation, was 1.1±0.5 GtC yr-1, while the global atmospheric CO2 concentration rate of growth was 3.9±0.2 GtC yr-1. The mean ocean CO2 sink being 2.9±0.5 GtC yr-1, with a global residual terrestrial sink of 4.1±0.9 GtC yr-1. The global atmospheric CO2 concentration rate of growth was lower in 2014 compared to the past decade (2005–2014), reflecting a larger land sink for that year, with a global atmospheric CO2 concentration reaching 397.15±0.10 ppm averaged over 2014.

In 2015, for the first time, the global monthly average concentration was above 400 ppm from March to May 2015 (Dlugokencky and Tans, 2015), while at Mauna Loa (NOAA) the seasonally corrected monthly average concentration reached 400 ppm in March 2015 (Le Quéré et al., 2015).

The first assessment of regional carbon budgets, RECCAP, which covered the period 1990-2009, was completed with the final synthesis papers appearing in Biogeosciences (Canadell et al., eds, 2015, Sitch et al. 2015).

From GCP and RECCAP the aspects that require additional research efforts include:

- The global partitioning Land vs. Ocean is well known (at least on decadal average). However, this does not stand at regional scale;
- Some fundamental discrepancies exist between methods to estimate regional carbon sinks that need to be addressed;
- There exist larger uncertainties in models at the regional level by comparison with global;
- There is a poor understanding of actual drivers of sinks at both global and regional levels;
- The uncertainty in emissions (both fossil and LUC) needs to be reduced;
- There are no annual estimates of LUC, which impact the capability to account for important processes (e.g., ENSO-related variability);

- There is a need to better understand and characterise the CO_2 versus the effect of climate (and land-use).
- The transport of carbon from land to the oceans needs to be included explicitly in the carbon budget.

Atmosphere
While atmospheric concentrations of the principal greenhouse gases (CO_2 and CH_4) can be estimated from space, their conversion into fluxes and their attribution remains a difficult task.

An example of this is estimation of the Australia natural CO_2 flux budget in 2010 using an ensemble of 4 results for Australia built with 2 alternative CO_2 products from GOSAT, 1 product from ENVISAT and surface measurements. This was of interest given production of organic matter (NPP) was abnormally strong in Australia in 2010-2011 associated with a strong La Niña event. This Australian anomaly is seen by the remote sensing of CO_2 (ESA CCI products), but not by the surface network.

However, there remains inconsistency within inversions as evidenced by estimations of the natural CO_2 and CH_4 fluxes reported in different papers (e.g., Pandey et al., 2016, Reuter et al., 2014, Howwelling et al., 2015, Peylin, 2013, Chevallier et al., 2014).

Clear differences between satellite and in-situ observations have also been identified when inferring regional natural CO_2 fluxes using the same inversion method and when applying different inversion tools to the same measurements (e.g., Basu et al., 2013; Chevallier et al., 2014, 2015; Reuter et al., 2014; Feng et al., 2016, Houweling et al. 2015). This clearly demonstrates that the accuracy and the spatial resolution & coverage of satellite and ground based measurements has to be improved in the future. It also demonstrates the need to develop improved GHG inversion algorithms in order to get consistent flux results.

Terrestrial
Estimates of the global terrestrial carbon sink are mainly based on the residual derived from the difference of the other components (atmospheric emissions minus atmospheric concentrations minus the ocean sink; the residual of this calculation is assumed to be the land sink). Even though this approach is perfectly valid, it does not provide any understanding of the land carbon cycle, as the different processes are not accounted individually, no validation is performed with independent estimates and errors allocated to it are partially from the other components within the calculation.

To address this, a number of initiatives using different approaches have been launched in the last years to obtain estimates of the terrestrial carbon sink directly from observations. For example, the FluxCom project aimed at delivering a best estimate ensemble product of carbon and energy fluxes from an ensemble of diverse data-oriented and FLUXNET based approaches. Fluxes collected in situ (e.g., FLUXNET network) are propagated at global scale by using EO estimates of LAI, FPAR, LST, and reflectances together with reanalyses and climatologies explaining the main seasonal cycles to infer the global fluxes.

The results demonstrate good progress as well as the complementarity of in-situ and remote sensing data. The inter-annual variability of the global carbon budget from this data-driven bottom-up product correlates well with the residual land sink and process-based models. Analysis further shows, that water availability is controlling the local processes dominantly, while at large spatial aggregation (continents to global) temperature is most strongly correlating with the inter-annual variation of the net carbon budget. Despite these robust results, considerable uncertainties are introduced by different driver data. For estimating the long-term (decadal) carbon balance predictor variables would be needed which relate to processes such as disturbance and regrowth, for an assessment of the site history. For instance, the following variables would be helpful:

- For Net Ecosystem Exchange (NEE):
    - Biomass and biomass change (e.g., from EE7 BIOMASS, GEDI lidar observations);
    - High resolution atmospheric CO_2 concentrations

- For GPP and NEE there is a need for knowledge of stress responses hence:
    - Fluorescence (e.g., GOSAT, FLEX)
    - Soil moisture
    - Geostationary observations to account for the diurnal cycles;

First results indicate that meaningful diurnal cycles can be generalized from FLUXNET data with a few remotely sensed variables. This information can be very informative for atmospheric flux inversion (see above). Clearly, further research is needed on both very short-time scales (diurnal cycles) and rather long-time scales (decadal mean and beyond).

To account for the variability of key processes a sample based approach at high spatio-temporal resolution maybe more important than full global coverage. However, this requires careful sample design to characterise the globe, taking advantage of infrastructure that is already in place e.g. NEON, TERN, ICOS, CERN.

Lastly there is a need to ensure that the data streams employed are consistent and are used appropriately. The combination of different data sets through data assimilation into land surface models has proven a valuable approach to reveal (and ultimately remove) inconsistencies among data streams and between data streams and models as shown in the ESA Carbonflux project (Kaminski et al. 2013). This type of work needs further investigation.

Ocean

The ocean represents a major sink globally of carbon absorbing around 25% of the total anthropogenic emissions. The uptake capacity of the ocean is large and is governed by physical and biological controls and the marine carbonate system, one component of which is the fugacity of CO_2 (fCO_2). fCO_2 is the partial pressure of CO_2 (pCO_2) corrected for the non-ideal behaviour of the gas, over the temperature ranges of interest within the global oceans. Knowledge of the spatial variation of fCO_2 (in the top few metres of the ocean) can be derived from the Surface Ocean CO_2 Atlas (SOCAT) while that on 3-D structure principally comes from repeat hydrography contained in the GLobal Ocean Data Analysis Project (GLODAP) database and through modelling efforts.

Given this information, current global ocean anthropogenic carbon stocks are reasonably well known, although some regions are better quantified than others, with such as the Southern Ocean, having a dearth of data. However, there are no pre-industrial ocean measurements to test against. The pattern of carbon sequestration into deeper layers can be inferred using proxies (e.g. CFC) and shows peaks at high latitudes, in eastern Mediterranean and the Red Sea. However, deep convection processes act at high resolution so are rarely characterised in sub-grid scale models. Knowledge of regional carbon stocks is limited although major exercises are dedicated to addressing this e.g. Southern Ocean Carbon and Climate Observations and Modelling (SOCCOM).

It is often said that '*In situ oceanographers* measure everything nowhere, *satellite oceanographers* measure nothing everywhere and *ARGO oceanographers* measure something somewhere'. Whilst doing each of these areas of science a large injustice, this statement tries to encompass the complexities and limitations involved in each of these measurement and observation techniques. It also tries to highlight the different spatial and temporal sampling that is possible with each of the different techniques. Thus a better understanding and characterization of the carbon cycle in the oceans and its variability that combines all of these observation approaches is of critical importance with the following challenges identified:

- Challenge 1 - Development of a "Steady-state" 3D "pre-industrial" baseline that reproduces the mean regional patterns well before meaningful time dependent assimilation can be carried out.

- Challenge 2 - Inclusion of coastal seas and ocean margins: Signals and matter turnover are not yet accounted for in ESMs and this means high resolution and further complexity is needed to resolve heterogeneous systems.

- Challenge 3 – Improved process understanding, in particular:
    - Deep water production and mixing;
    - Pollution effects;
    - Ocean acidification;
    - Glacial-interglacial variability/feedbacks;

- Challenge 4 - Verification of anthropogenic CO_2 emissions & emission reductions using oceanic constraints as an alternative to terrestrial fluxes. Oceanic constraints on regional C_{ant} budgets can be provided through variable surface pCO_2 but this requires improved atmospheric databases and better knowledge of the smoothing effect of slow air-sea gas exchange. Exploitation of the strong ocean constraint on the global carbon budget and total anthropogenic carbon sink would also be required.

5. Understanding of the carbon cycle – fluxes

Open questions on carbon fluxes

RECCAP synthesis (Peylin et al. 2013) indicates a total sink of 3 PgC/yr split between 1.32 on land and 1.79 in ocean but with large variability between different inversion systems (based on in-situ observations). Spatially this splits into sinks in the northern hemisphere on land, and a source in the tropics while the oceans exhibit a source in the tropics and sinks in both northern and southern oceans. The northern land sink location varies with respect to the inversion system used with N. Asia generally the strongest sink and Canada/Alaska and Europe being the weakest. More recent work using land surface and global ocean models reaches similar conclusions (Sitch et al, 2015), although these did not include consideration of land use or land cover change in the analysis, and using atmospheric inversions with GOSAT data also agree with these general observations (Houweling et al 2015). These recent results contrast with those of Stephens et al. (2007) and Schimel et al (2014).

Thus there remains a lack of consensus between top-down and bottom up estimates for the regional distribution of fluxes and the inclusion of satellite data does not seem to complement for the sparseness of the ground observation network in particular given the seasonal variations in satellite sampling introduced additional complexity and potential confounding factors. Assimilation of atmospheric CO2 observations into process-based models of the anthropogenic and biogenic components of the carbon cycle is a promising alternative, as it allows data gaps to be closed by process understanding and combination with further data streams as shown in e.g. the ESA Carbonflux project (Kaminski et al. 2013).

Besides the disagreement over regional distributions of natural sources and sinks, there is a need also to identify and quantify anthropogenic emissions consistently. Typically for CO_2, anthropogenic fluxes are fixed for global inversions, and only biogenic fluxes are optimised but this breaks down at smaller spatial scales: national statistics might be robust, but spatio-temporal distribution within the country less so. From a treaty/policy perspective it is of critical importance to develop a capability that allows the measurement and verification of carbon sources for policy-making and management, particularly given at least 70% of fossil-fuel CO_2 emissions are from urban areas (Duren and Miller, 2012) and that emission-reduction strategies are often planned on the city scale.

Being able to quantify emission inventories remotely and consistently on the scale of individual nations, would be of enormous policy relevance. Thus, there is an urgent need to develop advanced systems combining satellite and in-situ observations (EC, 2015) providing significantly more spatial information to resolve the sub-national and city scale e.g. a geostationary or high resolution imager, like the ESA candidate Earth Explorer Carbonsat concept, could represent an important contribution to such a system.

Ocean-atmosphere fluxes from satellite & in-situ observations and models

The Global ocean sink has been estimated from biogeochemical models, atmospheric inversions and inverse ocean interior estimates to be ~2 Pg C yr^{-1} (26 % of anthropogenic emissions, Le Quere et al. 2015) with variability estimated, using direct observations, to be ±0.31 Pg C yr^{-1} (Rodenbeck *et al.*, 2016). This variability is larger than that estimated by global climate models (~0.2 Pg C yr^{-1}). Knowledge of the exchange between atmosphere and ocean has seen significant advances in the last few years with improvements in automated *in situ* instrument capability and reliability and the compilation of quality controlled data through SOCAT. The availability of this dataset has enhanced our capacity to compute ocean fluxes. It is of primary importance to provide continuous support to this important initiative.

In addition, consolidated understanding of how to use near-surface temperature profiles has been developed. This can add 0.1 – 0.6 Pg C yr^{-1} to current global ocean sink estimates (Woolf *et al.*, 2016) and model simulations indicate this can reverse the direction of estimated fluxes. Advances in uncertainty accounting have been made but estimates vary ±30 - 100%, where the gas transfer velocity uncertainty dominates. This has been aided by new satellite Earth observations of sea surface salinity (e.g., SMOS, Aquarius), which have the potential to be used to determine total alkalinity and dissolved inorganic carbon via empirical algorithms (Land et al., 2015)

Given these advances there is mounting evidence to move away from 'wind only' proxy parameterisations of gas transfer and regional specific methods. However, *in situ*, model and satellite Earth observations are all needed. The development of novel open source tools (e.g., OceanFlux FluxEngine) help the scientific community to reconcile, for example, estimates of European shelf sea net sink which currently vary ± 60 % due to the use of different ocean area templates (Shutler *et al.*, 2016).

Nevertheless, there remains the need to:

- Improve analysis of uncertainties of satellite based products;
- Continue and expand *in situ* data collection and collation to underpin Earth observation work;
- Take advantage of the observational capacity offered by the plethora of recent and new satellite sensors (e.g., Sentinel series, SMOS, Aquarius, SMAP, GOCE).
- Fully explore the potential of EO, in-situ data and models, for studying ocean acidification and characterisation the vertical fluxes.
- Develop accurate methods to estimate the different variables of the carbonate system (e.g., pH, Total Alkalinity, pCO2);
- Explore the potential development of a space observing system to allow direct observations of carbonate system parameters;

Fluxes between land and atmosphere

Both IPCC and GCP estimate the global land uptake as the residual of other budget components (e.g., 2000-2009 estimate AR5: 2.6 ± 1.2 PgC/yr, with 90% confidence level; GCP: 2.4 ± 0.8 PgC/yr with 68% confidence level). Approaches based on Land

Surface Models, such as the work in the Trendy (Trends in net land atmosphere carbon exchanges) project (Sitch et al 2015), to date have shown large inter-annual variability and model spread of the same size as the uncertainty in the residual land sink. These therefore are not used as additional constraint on the global budget. Data-driven up-scaled products of fluxes from FLUXNET have the potential to provide an additional constraint here.

Carbon Cycle Data Assimilation approaches which integrate ecophysiological constraints from forward modelling with observational constraints from inverse modelling may represent a possible solution to address this complex problem. Data assimilation also has the advantage of allowing discrepancies between models and observations and among multiple data streams to be revealed. This contributes to improved consistency of models constrained by independent observations. It also allows the added value of observations to be assessed and uncertainty to be reduced. The ESA CarbonFlux project has demonstrated the potential of assimilating atmospheric CO2 observations together with estimates of soil moisture and FAPAR from satellite observations in a land surface model (Kaminski et al. 2013). Purely data-driven products have the advantage that they do not rely on theory and can provide complementary estimates which can be used for cross-checking and benchmarking (Beer et al. 2010, Jung et al. 2010, Bonan et al. 2012).

Further work in the development and testing of data assimilation systems with multiple data streams is therefore recommended *in parallel with* forward model developments such as those in the Trendy project and model-independent data-driven machine learning approaches.

In addition to improving knowledge of the land sink there is a need to:

- quantify emissions from fossil fuels with spatial and temporal resolutions higher than those currently available.
- improve understanding of emissions of CH_4 from wetlands and permafrost.
- understand the effect of the nitrogen cycle on CO_2 uptake and fertilisation or limitation processes.
- include lateral fluxes (mainly transport through rivers) in process models since the anthropogenic disturbance may be as large as 1.0 Pg C yr^{-1}.

6. Climate, humans and carbon cycle change

Observational evidence of carbon cycle changes and their attribution

Despite the importance of CO_2, our knowledge of the CO_2 sources and sinks has significant gaps and atmospheric CO2 continues to increase at a rate of approximately 2 ppm/year. An improved understanding of the CO_2 sources and sinks is needed for reliable prediction of the future climate of our planet (Buchwitz et al., 2015).

Evidence from studies from space and aircraft (Graven et al. 2013, Forkel et al., 2016), indicates that northern ecosystems are experiencing large changes in vegetation and carbon cycle dynamics. Analysis from Forkel et al. (2016) shows that the latitudinal gradient of the increasing CO2 amplitude is mainly driven by positive trends in photosynthetic carbon uptake caused by recent climate change and mediated by changing vegetation cover in northern ecosystems. This is corroborated by comparison of recent aircraft observations of CO_2 over the North Pacific and Arctic Oceans with data from 1958-1961 which show increases in the seasonal amplitude at altitudes of 3 to 6 km in the latitude band from 45° to 90°N. This is attributed to an increase in the seasonal exchange of CO2 by northern extra-tropical land ecosystems, focused on boreal forests (Graven et al. 2013). This change is substantially more than simulated by current land ecosystem models and it is hypothesised to signal large ecological changes in northern forests and a major shift in the global carbon cycle.

The same uncertainty in knowledge of sources and sinks is also true for methane. Methane records (Nisbet et al., 2014) show a rapid growth to the mid 1990s with a stasis in the early 2000s, before rising again since 2007 with very rapid growth from 2014. However, while clearly visible the mechanisms behind these increases are not well understood. These variations present significant latitudinal differences. Since 2007, Arctic methane rose more than the global growth rate in 2007, but since then Arctic growth has tracked global trends. Large emissions attributed to decaying methane hydrates have been reported from the East Siberian Arctic Shelf with emissions from wetlands, which are largest in summer/early autumn, a major control on the seasonal cycle. In the southern tropics, growth has been above global trends since 2007 as part of a regional 5-year rise in natural emissions. Global scale modelling of these methane observations suggests that in 2007, tropical wetland emissions dominated growth, with output from high northern latitudes also important. Since then, the increase has mostly been driven by the tropics (9 to 14 Tg $year^{-1}$) and northern mid-latitudes (6 to 8 Tg $year^{-1}$). Superimposed on this, emissions from human activities have increased since 2007 especially with the increased use of hydraulic fracturing (fracking) in the United States and the expansion of global coal mining, especially in China.

More data are needed to understand and resolve the divergence between top-down and bottom-up estimates, but the measurement network for methane concentration and isotopes is very thin. Better (spatially and temporally) and long-term measurements are essential to identify and quantify methane sources.

Over the oceans, SOCAT data represents an excellent source of historical information. There is a rapid increase in quantity of surface ocean fCO_2 data since the early 90s brought together quality controlled under SOCAT in recent years. The dataset providesgood coverage in the Northern Hemisphere, even though it is very sparse (both in space and time) in the Southern Hemisphere.

The Surface Ocean pCO_2 Mapping inter-comparison (SOCOM) initiative (Rodenbeck et al, 2015) used these measurements of surface-ocean CO_2 partial pressure (pCO_2) and 14 different pCO2 mapping methods to investigate variations in regional and global sea–air CO2 fluxes. In terms of inter-annual variability (IAV), all mapping methods estimate the largest variations to occur in the eastern equatorial Pacific. From a weighted ensemble average, results show an IAV amplitude of the global sea–air CO_2 flux of 0.31 PgC yr^{-1} (standard deviation over 1992–2009), which is larger than simulated by biogeochemical process models. From a decadal perspective, the global ocean CO2 uptake was estimated to have gradually increased since about 2000, with little decadal change prior to that. The weighted mean net global ocean CO_2 sink estimated by the SOCOM ensemble is -1.75 PgC yr^{-1} (1992–2009), consistent within uncertainties with estimates from ocean-interior carbon data or atmospheric oxygen trends.

Conclusion

While overall natural sinks of CO_2 can be tracked and the variation attributed to land or ocean regions at the continent and basin scale, it is difficult to provide higher spatial resolution than this (i.e. regional or local level). Similarly observed increases in the amplitude of the northern hemisphere seasonal cycle in CO_2 has been linked to increased terrestrial primary productivity, but the causes of this are not yet clear.

Major changes in the global growth rate of methane can be observed and there is some confidence in locations of (changes in) sources, but there is a little understanding of the causes of these changes (see Dalsoren et al. (2016) for discussion).

Terrestrial carbon cycle extremes: quantification, association with climate and implications

Global climate variations most often associated with feedback in the terrestrial carbon cycle include radiation, gradual warming, CO_2 (and N) fertilisation and change in precipitation patterns. Vegetation response to such climatic changes (Nemani et al., 2003), was found to have resulted in a 6% (3.4 Pg of carbon increase of net primary production globally, with tropical ecosystems exhibiting the largest increase (Amazon rain forests accounted for 42% of the global increase due to decreased cloud cover and the resulting increase in solar radiation). Drivers for these observed changes have recently been discussed in Zhu et al. (2016).

However, weather extremes may impact the structure, composition and functioning of terrestrial ecosystems, and thus carbon cycling and its feedbacks to the climate system. For instance, Ciais et al., (2005) examined the impact of the European heatwave in 2003 on primary productivity, and its consequences for the net carbon balance. Results showed a 30% reduction in gross primary productivity, which resulted in a strong anomalous net source of carbon dioxide (0.5 Pg C yr^{-1}) to the atmosphere and reversed the effect of four years of net ecosystem carbon sequestration. This reduction in eastern and western Europe was explained by a rainfall deficit and an extreme summer heat, respectively. An increase in future drought events could turn temperate ecosystems into carbon sources, contributing to positive carbon-climate feedbacks already anticipated in the tropics and at high latitudes.

Reichstein et al., (2007) carried out a synthesis of different studies addressing the impact of extremes weather events on the carbon cycle concluding that:

- The integrated effect of carbon cycle extremes on carbon balance is on the order of net carbon sink (1-3 PgC yr^{-1});

- Ecosystem responses can exceed the duration of the climate impacts via lagged effects on the carbon cycle.
- The expected regional impacts of future climate extremes will depend on changes in the probability and severity of their occurrence, on the compound effects and timing of different climate extremes, and on the vulnerability of each land-cover type modulated by management.
- Although processes and sensitivities differ among biomes, forest areas are expected to exhibit the largest net effect of extremes due to their large carbon pools and fluxes, potentially large indirect and lagged impacts, and long recovery time to regain previous stocks.
- At the global scale, droughts may have the strongest and most widespread effects on terrestrial carbon cycling.
- Comparing impacts of climate extremes identified via remote sensing vs. ground-based observational case studies reveals that many regions in the (sub-)tropics are understudied in terms of process understanding.
- Global inter-annual variability dominated by few extremes on small land surface area
- Not every climate extreme causes a (direct) carbon cycle extreme

The interconnected processes through which climate alters the carbon balance are, however, poorly understood and it is important to assess both the impact of extremes on the carbon cycle but also to fully understand the different processes involved. This requires support for well-defined regional investigations to allow a global up-scaling of the impacts of climate extremes on global carbon–climate feedbacks. Potential mechanisms to do this include data assimilation exercises with well characterised, consistent data products such as those from the ESA Climate Change Initiative (CCI) or in data cube projects.

Space-borne observations and carbon tipping points (or sensitive regions)

Potentially sensitive regions, vulnerability of pools have been identified due to limitation of CO2 fertilisation by water and nutrient constraints, the response of soil respiration and NPP to warming and moisture, permafrost thawing, fire and ecosystem responses to a variety of land-use changes (e.g. Raupach and Canadell 2008) and the existence of tipping points has been widely debated (e.g. Nobre and Borma 2008, Lenton and Williams, 2013). Improved understanding of regional GHG flux patterns, tipping-points and vulnerabilities requires long-term, high precision observations in the atmosphere and at the ocean and land surface both in situ and from space.

The principal advantages of space-based measurements include spatial coverage with frequent revisit times, global measurements over both land and ocean, high spatial resolution of some measurements (that may allow the discrimination of “centres of action” from background). Space based measurements already produce critical information about the carbon cycle (e.g., land cover type, phenology, photosynthetic activity, land use change, ocean colour (biological activity), sea state (significant wave height and whitecap formation), sea surface wind speed and direction, sea surface salinity, sea surface temperature, column integrated atmospheric XCO_2, XCH_4, precipitation, cloud/aerosol distribution). Of these satellite measurements, those over land have the longest continuous record (> 30 years). Ocean observations are of similar record length with sea surface temperature records spanning 25+ years. By comparison, space based measurements of the atmospheric carbon cycle are in their infancy. However, to improve space based observations as a reliable and efficient source of information the following enhancements to current systems are needed:

- Land:
    - Extend >30-m spatial resolution record and increase frequency from bi-monthly to weekly;
    - Add regional samples of high (< 1 - 10m) spatial resolution imagery;
    - Augment 2-D data with (sub-metre) vegetation vertical structure;
    - Quantify photosynthetic rates and vegetation condition (global, sub-km);

- Ocean
    - Improved spatial and temporal coverage and resolution (< 250 m) of coastal margins to constrain carbon/nutrient export from land to ocean;
    - Hyperspectral observations of coral reefs and other threatened ecosystems;

- Atmosphere
    - Global measurements of CO_2 and CH_4 at 2-5 km^2 resolution, weekly
    - Complementing the above observations with time resolved observations of CO_2 over diurnal cycle
    - Improved coverage of high latitudes, partially cloudy regions, night side
    - Other challenges for GHG measurements include:
        - Small concentration gradients require high precision and accuracy;
        - Frequent revisit times are essential, since the atmosphere moves;
    - Other trace gas measurements for attribution (CO, NO_x, DMS, H_2S, OCS)

To further enhance existing space based systems and move forward a global infrastructure requires international cooperation incorporating both broad swath, high resolution low earth orbit missions that cover the entire globe and geostationary missions to capture the full diurnal cycle and rapidly varying features.

Towards an European operational observing system to monitor fossil CO2 emissions

The European Commission (EC) recently brought together key experts to define the requirements to develop an operational observing system to monitor fossil CO2 emissions (EC, 2015) and provide independent estimates of fossil CO_2 emissions in support of national inventories. The objectives of such a system are to provide an internationally accepted set of measurement data to improve consistency and inter-comparability between inventories.

Such a system would also allow strong emission sources and sub-national patterns of emissions to be identified to augment the granularity of current emissions inventories, which are constrained by the granularity of economic and other data. In addition, it would provide a capability to quantify emissions trends at the scale of regions within countries, and potentially of cities and emissions hotspots.

Specific measurements of atmospheric CO_2 from space and dedicated in-situ networks are needed for improving fossil CO_2 emissions estimates. Over the next decade, a succession of partially overlapping missions with a range of CO_2 and CH_4 measurement capabilities will be deployed in low Earth orbit. Each mission has been conceived with unique capabilities, designed to improve the measurement precision and accuracy, as well as the spatial and temporal resolution, and coverage to improve understanding of surface fluxes of GHG from the continental to local scales.

Current (and past) space-based CO2 missions (e.g. SCIAMACHY, GOSAT, OCO-2) were not designed to quantify anthropogenic emissions. They were designed to estimate natural fluxes on regional scales. This is intended to continue, in Europe, with future missions planned or under development, such as MicroCarb and MERLIN. The OCO-3 instrument, which is scheduled for deployment on the International Space Station in 2018, can map out a selected number of city-scale CO2 emission hot spots at high spatial resolution, but the number of targets and repeat opportunities are limited.

To achieve the objective above requires an increase in the density and spatial resolution of atmospheric CO_2 measurements from satellites, since fossil fuel emissions are concentrated over small areas. The EC report (EC, 2015) recommends development of an observation system including:

1- In the near term, before 2025, a carbon mission to provide the capacity of quantifying fossil CO_2 emissions by delivering XCO_2 with high resolution (typical pixel size of less than ≈3 km in size), imaging capabilities, precision of ≈ 1 ppm for individual XCO2 measurements with systematic errors < 0.5 ppm, and global coverage.
2- In the long term (by 2030) a set of (European and non-European) carbon missions for the frequent detection, quantification and monitoring of emissions. This envisages consideration of combined active and passive space-borne sensors and the close coordination internationally of space-based resources to provide continuity and resiliency to losses of data from individual satellites. This close coordination will provide greatest benefit if space-based measurements could be coordinated with each other and with the surface in-situ monitoring network, to produce a global monitoring system with the resolution and coverage needed to provide policy-relevant information. To meet this objective, the measurements will need to be calibrated against internationally recognized standards.

The report included also the following recommendations:

- The development of a Fossil Fuel Data Assimilation System (FFDAS) combining: Emission inventory information, Column integrated satellite CO_2 measurements, possibly complemented by satellite measurements of combustion tracers related to fossil CO_2 emissions (e.g., CO) and in-situ atmospheric measurements of CO_2 and tracers (e.g., CO, 14C).

- The development of emission inventories to become available on an operational basis at detailed spatial (1 x 1 km) and temporal (hourly) resolution, with a near-real-time production capability. This capability exists on a research basis in major European inventory groups but will need to be developed for operational requirements.
- To build urban monitoring networks for selected European large cities to evaluate independently satellite-based city-scale emission estimates. 14C measurements should be deployed at a set of approximately 50 atmospheric CO_2 monitoring stations across the European continent, with higher density over regions with high emissions.
- To maintain the ground based Total Carbon Column Observing Network (TCCON) and expand its coverage in cities and areas with high fossil CO2 emissions.

In response to this report ESA and EC have initiated a dedicated task force of experts to establish programmatic plans for the development of CO_2 mission as part of European Copernicus programme.

7. Key problem areas and new frontiers

Wetland emissions

Wetland emissions represent the largest and most uncertain source in the global CH_4 budget. Wetlands have been defined as “inundated or low water table soils where anaerobic conditions lead to methane production” (EPA, 2010). This encompasses a large range of different ecosystems including mixed landscapes of sparse shrubs, evergreens, and temporary water, fen-dominated environments, swamps, marshes, bogs, etc., where the processes that govern the methane emissions are different and thus difficult to quantify.

Most recent estimates for global wetland emissions (Kirschke et al., 2013, Saunois et al. 2016) for 2003-2012 are consistent for bottom-up models (184 Tg/yr) and top-down inversions (170 Tg/yr). However, results show significant inter-annual variability and no clear trend in the global wetland emission change, thus requiring other sources to explain the sustained current atmospheric growth.

Uncertainties in the modelled methane emissions (Melton et al. 2013, Wania et al. 2013) from wetlands are due to wetland extent (40-50%), to model structure and parameters, and to climate forcing. Information derived from satellite, specifically wetland extent and dynamics, can provide an important contribution to reduce current uncertainties, if they can be generated reliably and consistently.

EO-based global databases of wetland extent and dynamics exist, at different spatial resolutions and time periods covering up to 15 years, based on multi-satellite approaches (Bergé-Nguyen and Crétaux, 2015; Nakaegawa, 2012; Pekel et al., 2015; Kuenzer et al., 2013; Santoro et al., 2015; Sippel et al., 1998; Prigent et al., 2001, 2007, 2012; Papa et al., 2010, Schroeder et al., 2015). However, the information provided by these types of products (wetland extent and dynamics) and the information required by models may differ substantially, as inundated areas and wetlands (as methane sources) are not equivalent.

There have been some attempts to exploit satellite data to constrain emission models. As an example, Saunois et al . (2016) tested different process models forced with the same wetland extent product: a merge of remote sensing based observations of daily inundation from the Surface WAter Microwave Product Series Version 2.0 (SWAMPS; Schroeder et al., 2015) with the static inventory of wetland area from the Global Lakes and Wetlands Database (GLWD). Results did not show a global trend on average for the 2000 to 2012 period; hence, other sources have to explain the sustained atmospheric growth since 2007 (~+6ppb/yr, +13 ppb/yr in 2014).

In conclusion, while wetland models exist there are large uncertainties corresponding to model structures and parameters but also to external drivers, i.e., climate and wetland extent. Global databases of wetland extent and dynamics exist, at 25 km spatial resolution covering more than 15 years, based on multi-satellite approaches and new products are being generated (e.g. Schroeder et al. 2015) but there is a need to downscale these datasets to higher spatial resolution, merging them with DEMs or with Sentinel 1 and 2 data. This requires very careful handling of the satellite information over time, to produce the consistency and reliability in the time series needed for model-data intercomparison.

Current satellite products provide only a piece of the required information (e.g., inundation or wetland extent) and this is not directly linked to the different wetlands emission patterns and processes. Thus, emissions from the different inland-water systems need to be considered in an integrated manner to avoid double and/or miss-counting. The contribution to this from EO involves the construction of a high resolution map for the different inland water systems, complemented by expert knowledge for wetland allocation with the inclusion of environmental information to the wetland extent for a more accurate estimate of the CH_4 fluxes. This entails the strengthening of the dialogue between wetland ecologists and the remote sensing community and more observations to constrain the methane flux densities modelled for the different inland water systems.

Carbon in the tropics - a resolved question?

The uncertainty surrounding the location of sources and sinks and their dynamics requires better estimates of the carbon stocks and fluxes, in particular in the tropics given the postulated importance of tropical forest in regulating variation in the carbon cycle. Recent efforts have been targetted at improved in situ observations (through the efforts of e.g. RAINFOR, AfriTRON, TROBIT, T-FORCES) and building on these efforts to establish carbon assessments through e.g. AMAZONICA. In addition, there have been renewed efforts to generate pan-tropical maps of aboveground biomass uisng satellite observations (Saatchi et al., 2011 and Baccini et al., 2012). However, comparison of these products (Mitchard et al., 2013) showed spatial and amplitude differences but more importantly a markedly divergent estimate of the forest carbon density from ground plots and the satellite products (Mitchard et al., 2014). Part of the problem is linked to the fact that maps based on extrapolation of tree height do not produce true

AGB maps, as wood density varies in space. Therefore, it is critical to consider the spatial variations in wood density and forest structure. To address this issue plot-weighted techniques have been developed to *fuse* and *anchor* the Baccini & Saatchi maps to field plots (Avitabile et al., 2016). Results show better agreement with independent point data, even though uncertainties far from the plots are still high. While better observations of above ground biomass are critical, there is a need to complement these with observations below ground (soil and roots) and of the atmospheric signals of CO_2 and CH_4 to permit estimation of carbon stocks and fluxes.

Thus improvement is needed in:

- Methods and techniques that maximise the synergy between the in situ plots and satellite estimates e.g. through data assimilation.
- Characterising ecotype-specific allometric equations (height-biomass) and wood density. Terrestrial Laser Scanning provides a potential solution for allometry as well as to supplement the in situ inventories. Increasing the number of TLS measurements would be very useful especially given the upcoming statellite launches of BIOMASS, NISAR and GEDI.
- Integration, communication and coordination between in situ and satellite communities especially for biomass estimation. Ground plot data forms an integral part in the inversion of EO data to biomass estimates and in the verification of the resulting products. Networks such as CTFS-ForestGEO and ForestPlots provide such data on global scales. For use by satellite teams these networks need to be better integrated (e.g. standardisation of products, harmonisation of data streams, etc.) and to do so EO communities need to support their long term funding beyond 2018.
- Preparing for future EO missions such as GEDI, BIOMASS and NISAR. It is imperative to start the preparation of the exploitation of these missions and their potential synergies also with other observations systems (C, L and X band SARs, Optical). For instance, by developing models and data assimilation systems capable of exploiting these observations in a consistent way. This includes the development of appropriate observation operators that simulate exactly the quantity that is observed from space (see also Kaminski and Mathieu, 2016).
- Methods to scale up from in-situ measurements to single plots in the terrain (e.g., TLS), to airborne lidar observations and satellite regional and continental estimates of carbon stock and fluxes estimates. Improved upscaling will be very useful to better validate satellite estimates as well as to compute uncertainties.

Thawing, Greening, Browning, and Other Issues Affecting C Dynamics in the Permafrost Region

The Arctic is a sink for atmospheric carbon dioxide (CO_2), absorbing up to 25% of the Earth's carbon, but it is also a substantial source of methane (CH_4) to the atmosphere, mainly because of the large area covered by wetlands and lakes (McGuire et al. 2009). In a warming Arctic, with longer and warmer growing seasons, may accelerate the microbial breakdown of organic carbon stored beneath and within permafrost of high-latitude ecosystems but estimation of the magnitude and timing of CO_2 and CH_4 release to the atmosphere from these regions remains highly uncertain. Increased release of CO_2 and CH_4 into the atmosphere has the potential to significantly impact the global carbon and water cycles and global ecosystems.

The Permafrost Carbon Network (PCN) was developed to address this uncertainty as part of the multi-million US dollar, cross-disciplinary Study of Environmental Arctic Change (SEARCH) research project to help connect science with decision makers. The results of Phase 1 of this initiative have:

- Produced a new dataset for estimating organic carbon storage to 3 m depth in soils of the northern circumpolar permafrost region (Hugelius et al., 2013);
- Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps (Hugelius et al., 2014);
- Analysed the thermal dynamics of permafrost and response to climate change in Earth system models (Koven et al., 2013);
- Investigated permafrost thaw and resulting soil moisture changes impacts on projected high-latitude CO_2 and CH_4 emissions (Lawrence et al., 2015).
- Assessed the carbon balance of Arctic tundra (McGuire et al., 2012) and the vulnerability of permafrost carbon to climate change (Schuur et al., 2013, 2014, 2015);

The second phase of the Permafrost Carbon Project proposes:

- Benchmarking and improving interactions with the Earth System Modelling Community;
- Geospatial analysis: addressing the scaling issues of PCN synthesis activities
- Assessment of the greening versus browning of the Arctic;
- Use of carbon isotope approaches to understand rates and pathways for permafrost C mobilization and mineralization;
- Generation of circumpolar primary and derivative data products.

The ability to estimate and predict the amount of carbon release is hampered by the fact that models do not account for some important processes e.g. permafrost but also by a lack of data to parameterize and constrain the sensitivity of models to environmental change. Evidence suggests that rapid permafrost thaw will occur throughout the Arctic. This process, called thermokarst, alters surface hydrology, contributing to further thawing and even mass erosion. Due to these localized feedbacks, permafrost degradation occurs at a much faster rate than would be predicted from changes in air temperature alone. Where models contain permafrost as a component, air temperature is used to estimate permafrost thaw from the surface downward in a simple fashion. However, in order to accurately quantify carbon emissions, more complex approaches are required to also link permafrost thaw to ground subsidence and soil moisture dynamics.

To improve assessment and reduce uncertainty regarding the carbon cycle response of the Arctic region under projected changing climate conditions, it is important:

- To estimate the rate and extent of surface permafrost degradation by linking field, satellite and modelling approaches;
- To comprehensively observe and understand the processes that drive carbon dynamics and incorporate this knowledge in uncoupled and fully-coupled carbon-climate models;
- To understand the magnitude, timing and form of the permafrost Carbon (e.g., methane) release to the atmosphere;
- To improve/develop field and satellite remote sensing datasets for model evaluation.

A recent paper (McGuire et al., 2016) provides a summary of recommendations for permafrost-carbon related processes in Earth system models and the related variables and parameters to be observed.

In terms of the needs for EO data, at the ESA Permafrost User Workshop in Frascati, 11-13 February 2014 a white paper was prepared by the community in response to the WMO-Polar Space Task Group (Bartsch et al., 2014). The paper advocates for the use of satellite data to:

i) identify “hot spots” of surface change and thus advice on extension of *in situ* monitoring network;
ii) support modelling of sub-surface conditions;
iii) provide higher resolution (spatial and temporal) measurements in the proximity of long-term *in situ* monitoring sites (’cold spots’) and north-south transects;
iv) place the *in situ* measurements into a wider spatial and temporal context;
v) map and monitor systematically at high-resolution the coastlines in high latitudes, and
vi) generate regional scale analysis of permafrost disturbances and their rates and trends.

About 50 locations (‘cold spots’) have been identified where permafrost (Arctic and Antarctic) *in situ* monitoring has been taking place for many years or where field stations are currently established (through, for example the Canadian ADAPT program). These sites have been proposed as part of the community white paper (Bartsch et al., 2014) to the WMO Polar Space Task Group (PSTG) as focus areas for future monitoring by satellite data.

To support upscaling/downscaling monitoring of permafrost regions and the spatial extrapolation/interpolation of field measurements in those regions, more investigations using a combination of SAR, optical, and thermal image products acquired at different spatial resolutions are needed. For SAR, this means combining wide-swath mode, strip-map mode, and spotlight mode and different radar frequencies. The objective is to collect “pure” signatures of different land cover units (vegetation and bare surface types, lakes, rivers) and their variations due to changing environmental and meteorological conditions in key regions with sufficient infrastructure for ground measurements. The reason is that land cover types can change at rather small spatial scales, on the order of a few tens of meters. Hence, “clean reference” signatures are needed to improve the retrieval of bio-geophysical parameters from coarse-resolution radar images, which provide the necessary spatial coverage and temporal resolution to monitor long-term trends in land-cover changes.

Regional interferometric SAR (InSAR) studies are needed over cold spot regions to quantify rates and trends in surface subsidence related to permafrost thaw. A key to monitoring understanding and permafrost dynamics is the exploitation of decadal scale time series of imagery from multiple satellite/sensor systems, such as combinations of Landsat with Sentinel-2 time series.

The Arctic Ocean and sea-air carbon exchange

The atmosphere-ocean (air-sea) movement (flux) of greenhouse gases is a critical part of the climate system and a major factor in the development of the oceans. The Arctic Ocean contributes only ~1% to the global ocean volume but it is thought to account for 5-14% of the total oceanic sink for anthropogenic carbon dioxide (CO_2) (Bates and Mathis, 2009), a process which begins via air-sea gas exchange.

The inhospitable and heterogeneous nature of the Arctic make if difficult and expensive to rely solely on in situ observations for monitoring and understanding its changing environment. Synergistic use of satellite observations, in conjunction with in situ data and models, provide a solution to providing more spatially complete observations. Such data can be used for driving innovative process studies (e.g. Land et al., 2013), climate model evaluation and data assimilation, and developing monitoring methodologies. Atmosphere-ocean CO_2 gas exchange is comprised and controlled by chemical, physical and biological processes and satellite Earth observation can be used to support the study of all three of these, in relation to both the forcing and the impacts.

Issues highlighted by the international community (e.g. Hofman et al., 2014) where satellite Earth observation can be exploited in relation to Arctic atmosphere-ocean gas exchange research include:

- the need to understand and characterise changes in atmosphere-ocean exchange of gases between the Atlantic and Arctic waters (i.e., at the Arctic gateways);
- characterising phytoplankton bloom dynamics (i.e. phenology, succession and poleward movement, e.g. Winter et al., 2013) and their impact on atmosphere-ocean gas exchange (e.g. Shutler et al., 2013) at the gateways in the Arctic ocean;

- studying the impact of increased air-sea gas exchange due to loss of Arctic sea-ice and the exchange within ice-flows and the marginal ice zones (e.g. using Sentinel1A),
- studying the change in fresh water inputs and dissolved inorganic carbon (DIC) from Arctic rivers and melting sea-ice, and their impacts on air-sea gas fluxes and the net CO_2 sink (e.g. changes in salinity, fresh water pools, increased DIC inputs from rivers);
- the study of marine aerosols and CCN generation within Arctic waters;
- studying and characterising the long term variability of the uptake of CO_2 in Arctic and sub-arctic waters (e.g. using the ESA SST, ocean colour Climate Change Initiative data in conjunction with GlobWave and in situ data).

Carbon exchange of semi-arid regions

While tropical forest has been the focus of most carbon research, semi-arid regions are important for understanding the observed Inter-AnnualVariability (IAV) in atmospheric CO2. They play an important role at global scale representing a significant contribution to the variability of global NPP.

The year of 2011 was observed to have the highest land sink value since 1959 *(*Le Quéré et al., 2015*)* and the highest value of global NPP. Much of the temporal and spatial variability observed in vegetation carbon uptake is a function of the coupled pattern of El Niño/Southern Oscillation (Bastos et al., 2013), Results show that the cumulative effect of subtropical regions in the Southern Hemisphere, appears to have a strong influence on the variability of global NPP. The nature and the strength of the relationship between ENSO and global NPP depends strongly on changes in soil water balance and water availability and their role in controlling the dynamics of vegetation productivity. This dependence is most easily seen in semiarid regions, as they can respond very rapidly to changing environmental conditions, during El Niño/La Niña events and the effects of climate extremes are the most severe (Poulter et al., 2014).

For example, Detmers et al. (2015) reported on a large enhanced carbon sink over Australia from the end of 2010 to early 2012 detected using GOSAT, which coincided with a strong La Niña episode. This La Niña event produced record-breaking rainfall and large-scale vegetation growth in the arid central region, leading to a strong carbon uptake by the land biosphere, corresponding to 1000% of the total annual net ecosystem production. The vegetation provided ample fuel for the biomass burning in the dry season of 2011, leading to a large increase in biomass burning emissions in Central Australia, also detected in the GOSAT XCO_2 IAV. After the 2-year period of increased carbon uptake drought conditions once again returned at the end of 2012, leading to a return to pre-existent carbon uptake by the land.

Such work provides insight into how the biospheric uptake of carbon responds to events such as droughts and floods. This rapid response in semi-arid regions also constrasts with previous works suggesting that drought in Amazonia could be one of the major drivers of global productivity variation (Cox et al., 2004, Zhao and Running, 2010).

If the objective is to understand how biospheric uptake of carbon responds to climate changes, then further work on semi-arid systems is warranted. The combination of observations on atmospheric composition (e.g. with GOSAT) with key variables such as soil moisture and vegetation productivity, and potentially also solar induced fluorescence (SIF) (e.g., in a Carbon Cycle Data Assimilation System, as demonstrated in Kaminski et al., 2013), promises to provide insight into how changes in net ecosystem exchange of carbon are translated into changes in XCO_2.

8. Advancing towards an integrated approach

The insights above have been provided primarily through research activities. However basic research cannot be the only basis to consistently produce status reports on the carbon cycle. The translation of this research into a system that regularly produces updates on the status of the carbon cycle across multiple temporal and spatial scales requires the consideration of approaches to develop a comprehensive global carbon observing system. Such a system, builds upon the research but requires coordination of activities across traditional domains (land, ocean, atmosphere), spatial and temporal scales and observation methods (satellite, in situ, modelling) and long-term investment to construct and support it. Such a development cannot be developed either from scratch or overnight and requires efficient exploitation of existing infrastructural investment as well as being anchored in legislative commitments/requirements for such a system (e.g. feeding into national and sub-national carbon accounting requirements, or use for separating natural and anthropogenic fluxes and attributing them spatially and temporally).

Such a holistic and system approach has been advocated through international fora such as GEO (Ciais et al. 2014, GEO, 2010) and this in turn has produced responses at national (e.g. NASA Carbon Monitoring System, CMS 2014) and international levels (see WMO, 2014, CEOS 2014). The recently accepted GEO Carbon Initiative (Bombelli et al. 2014) aims at coordinating between existing structures including CMS, IG3IS, and research efforts such as RECCAP, the Global Carbon Budget and Urban and Regional Carbon Management initiatives of GCP and infrastructural networks such as ICOS, NEON and TERN to develop a mechanism which allows annual updates at regional and global levels in a manner that is consistent with national, subnational and local accounting schemes. In doing so it has as objectives:

- provide more inclusive coordination among the main actors monitoring carbon cycle and GHG at global level,
- develop a connected and interoperable system of systems for carbon cycle and GHG observations and analysis,
- provide decision makers with data, information and products needed to address climate policies and tackle global change

The development of such a system requires commitment from the research community, international institutions, GEO participating countries and observers and funding organisations to realise the objectives set out in the initial concept.

9. Summary of the breakout sessions

The talks summarised above considered specific issues on particular aspects of the carbon cycle with an emphasis on the contribution from satellite observations. Following from these the breakout discussions were designed to cross-cut the topical sessions with an emphasis also on domain interaction. The objective of these sessions was to produce recommendations to the community, GCP and CEOS.

Breakout 1: How do we use models and observations together to improve carbon cycle predictions (leads: Bernard Pinty, Peter Cox, Markus Reichstein)

The interface between observations and models and how they may be best combined to improve carbon cycle predictions is important to allow the following questions to be tackled effectively:

- *Carbon Sinks* – (1) How big is the tropical vs NH land C sink; (2) Where is the NH land C sink? And why does it exist?
- *What is the decadal scale predictability of the land carbon sink/ocean carbon sink/atmospheric CO_2? Can we do it 5 years ahead?*
- *Regional ocean carbon fluxes* - what causes their variability?
- *What do we need to verify CO_2 emissions by 2023?*
- *Methane* - What is the role of wetlands and permafrost thaw on the methane budget?

Carbon stocks and fluxes

To address these issues requires concerted effort to reduce uncertainties in future changes in carbon fluxes between land, atmosphere and ocean (including riverine fluxes) and to understand the responses of carbon fluxes to climate variability and extremes. Most Earth System Models now include representations of the carbon cycle and the development of adjoint and tangent linear models (e.g. for BRTHY, JSBACH, JULES, ORCHIDEE, DALEK) and both data assimilation and model-data fusion techniques are targeted towards improving the interface between models and data. The key challenges are then to effectively exploit the available long-term in situ atmospheric CO_2 and CH_4 measurements in tandem with existing EO data on column integral CH_4 and CO_2 (GOSAT) and on land surface properties (e.g., FAPAR, soil moisture) as well as preparing in advance for new space-based information such as the provision of spatial information on biomass (e.g. BIOMASS, GEDI, NISAR) and photosynthetic activity/fluorescence (e.g. FLEX, Sentinel-4/5/5p). However, these space data sources need to be considered collectively with hyper-intensive surface measurements as well as information on mortality. This challenge includes the provision of observation operators linking the model state variables to the observables.

In addition, changes in stocks, in particular, disturbance are equally important as improved knowledge on the stocks themselves. It is through these that we can start to consider the prediction of decadal changes in C storage to specified uncertainty (land/ocean C), have greater expectation of identifying more precisely the location and magnitude of sinks and start to consider more complex interactions with other cycles e.g. understanding the role of water use efficiency.

In addition to considering the 'traditional' interfaces for data-model combination, as demonstrated by Rayner et al. (2011) for quantifying future terrestrial carbon fluxes based on a model calibrated by contemporary data, there is a need to explore more innovative approaches such as the idea of emergent constraints. The concept of Emergent Constraints is to use Earth System Models to identify the relationships between observable contemporary variability (or contemporary trends) and future sensitivity. Emergent constraints relate observable variability (Constraint) to future sensitivity, using an ensemble of Earth System Models (Emergent) to reduce uncertainty in the real Earth System. Examples relevant to carbon cycle feedbacks in Earth System Models include:

- use of long term sensitivity of the tropical land carbon storage to climate warming and the short-term sensitivity of atmospheric carbon dioxide (CO2) to interannual temperature variability to look at carbon loss from tropical land due to climate change (Cox et al 2013, Wenzel et al 2014)
- use of sensitivity in the CO_2 seasonal cycle amplitude to GPP and mean annual CO_2 caused by increase in size of fluxes, or increase in phase lag between GPP and respiration (Graven et al. 2013) to look at CO_2 fertilization of photosynthesis.

Recommendation B1_1: Make better and wider use of EO data to evaluate ESMs simulations (especially on annual to decadal timescales) via data assimilation and model-data fusion techniques targeted towards improving the interface between models and data. In particular focus on effectively exploiting the available long-term in situ atmospheric CO_2 and CH_4 measurements in tandem with existing EO data on column integral CH_4 and CO_2 (GOSAT).
Recommendation B1_2: Prepare models and observation operators in advance for new space-based information such as the provision of spatial information on biomass (e.g. BIOMASS, GEDI, NISAR) and photosynthetic activity/fluorescence (e.g. FLEX, Sentinel-4/5/5p).
Recommendation B1_3: Develop datasets that consider space data sources collectively with hyper-intensive surface measurements.
Recommendation B1_4: Explore Emergent Constraints within ESMs that relate future changes in the carbon cycle to variations and trends that can be observed now.
Recommendation B1_5: Derive information on tree mortality and disturbance from BIOMASS PDFs.

Extreme events

The carbon cycle can be strongly influenced by such extreme events e.g. European heatwave of 2003. Extremes are also important for society given that their frequency of occurrence may be increasing and their indirect impacts e.g. air pollution events are more likely in the future. However, most carbon cycle models have been designed with understanding of the longer-term behaviour of natural sinks and fluxes in mind, and are thus not necessarily tuned to deal with extreme events. A difficulty is that extreme events by definition do not happen frequently and tend to have regional rather than global impacts. This actually presents an opportunity which ties in with the relatively short time series but spatial comprehensiveness of space data, namely to trade space for time by studying extremes occurring within the satellite record at regional levels. If insight can be gained, then responses to extremes can be used to constrain the sensitivity of the carbon cycle to longer-term trends in climate and atmospheric composition.

Recommendation B1_6: Conduct exercises to study regionally defined extreme events e.g. European heatwave 2003, Australian Millennial drought, Indonesia El Niño fires/pollution using spatially comprehensive observations from space to understand behaviour of extremes on carbon cycle and their use for extrapolation.

Regional Ocean carbon fluxes

While global flux estimates are in reasonable agreement, regional fluxes are much poorer because most models predict rather uniform flux while measurements suggest more variability. This implies there are missing processes in models and work is thus required to understand how to accommodate for the observed variability by looking for its drivers.

Recommendation B1_7: Conduct exercises on generating regional flux information over oceans e.g. SOCCOM including satellite data where relevant to elicit model processes responsible for flux variability.

Land-ocean fluxes

Land-ocean fluxes are a missing element in carbon cycle models and observations are relatively limited for these C fluxes. A key priority is the variability rather than the absolute magnitude. A possible solution is to explore rainfall and its link to water colour (as a proxy for DOC). The potential use of SMOS, SMAP, S3, PACE and other missions to infer information on colour and salinity changes in large river plumes needs to be investigated.

Recommendation B1_8: Examine the use of different data sets to generate dynamic (time-series) of land to ocean fluxes (e.g. from large rivers into the ocean) e.g. the possibility to determine DOC in large rivers using rainfall and water (ocean) colour and how this influences the marine carbonate system.

Methane

Improved information on methane is attractive for policy and scientific reasons. The key priorities are improved knowledge of sources and sinks in particular from wetlands and permafrost thaw. The focus of this work should be on closure of the methane budget.

Recommendation B1_9: Establish long term coherent data sets over wetlands and permafrost to improve knowledge of sources and sinks and help close the methane budget.

Measurements, Data and Modelling

Addressing these issues above requires a special focus on the consistency of EO measurements versus surface observations and on improving the compatibility of data products and models which requires a continuous communication interface between modellers and observers (especially EO) as well as improvements in data access and development of common data formats with the appropriate information on uncertainty. These tasks should be conducted with an emphasis on training next generation of scientists in EO, in situ and model domains.

At the same time as tackling the above there is a need to consider the data required to establish independent systems for the verification of CO_2 emissions. This involves the design of optimal observing systems which examines the interface between space and surface observations, different forms of space data (LEO vs Geostationary) taking into account existing networks and satellites. This also requires re-evaluation of the capability of models to perform such an assessment, the development of simple ESM for reanalysis and methods for the ingestion of high density data taking into account their correlation/variances.

Recommendation B1_10: Examine space, in situ data and model consistencies including product compatibility, appropriateness and access via an active communication between modellers and observers.
Recommendation B1_11: Encourage the space, in situ and modelling communities collectively to invest in training the next generation of modellers and observers.
Recommendation B1_12: Evaluate the design of optimal observing systems in the context of existing network and data distributions.
Recommendation B1_13: Evaluate the capability of current models and the need for new models to ingest high density data and use it for verification of CO_2 emissions.

Breakout 2: How can we reconcile observations over oceans, land and atmosphere and ensure consistency of carbon flux calculations? (leads: Andy Watson, Marko Scholze)

Flux calculations traditionally are generated within domains with little consideration of consistency cross-domain. If the objective is to improve regional carbon cycle budget calculations then observations over land, ocean and atmosphere need to be reconciled. Reconciliation requires consideration of the treatment of uncertainties, in particular, biases in each domain, examination of potential synergies in observations between domains, the fluxes between domains, tools used currently to reconcile observations and finally evaluation of where improvements can be made, in particular, where space-based data can contribute.

To do this there is urgent need to:

- improve the combination of carbon cycle models (ocean, atmosphere and land) and their interfaces, as well as the EO datasets and in-situ observations they depend on. The priorities for this work include:

    - Generating a full process-based land flux for the global budget rather than relying on a residual for budget closure.
    - Estimating the transfer of carbon from land to the oceans in key areas such as lakes, estuaries, coastal ocean fluxes.
    - Focusing the research community on long term understanding and leaving political/decision-making requirements for short-term attribution needs to be addressed by dedicated agencies.

Recommendation B2_1: Concentrate effort on the development of global models with common understanding of terminology between domains for long-term understanding with a key priority on process-based land fluxes.

Recommendation B2_2: Develop methods for fully characterising the land-ocean lateral flux, taking account of available data sources.

- establish a common understanding of terminology among communities. Definitions of key parameters and assumptions behind their derivation over different reservoirs (e.g., ocean vs. atmosphere) are often not comparable. This applies also to the interfaces between in situ and space observations and between space observations and models.

Recommendation B2_3: Establish a common lexicon for key parameters in the carbon cycle across domains (observation-model, and land-ocean-atmosphere)

- improve regional understanding and quantification of the land sink and its related exchanges with the ocean and the atmosphere. This should include consideration of data assimilation with multiple data streams, use of model ensembles, benchmarking and model integration across domains.

Recommendation B2_4: examine cross-domain model integration, multiple data stream assimilation and model ensemble use.

- improve the consistency between global and regional understanding and quantification of the carbon cycle. While significant progress has been made at global scale through continuous updates to the global carbon budget, the consistency between this and regional efforts needs urgent attention. Progress on regional understanding should target key priority areas where data or understanding are missing e.g. The Arctic, Indonesia, The Southern Ocean;

Recommendation B2_5: aid the development of models, observation operators, and data assimilation methods (see B2_4) by sponsoring/conducting regional intensive studies.

- improve the exploitation of spatially comprehensive products provided from satellites. This comprises in part ensuring consistency between products and reconciling existing methods/data products on the part of the EO community, but also consideration of the interface between the EO community and the carbon cycle community. Thus space agencies should coordinate their efforts to:
    - reconcile by product intercomparison existing data products and ensure products are consistent across products and each data set has full traceability of its development and includes where possible per-pixel uncertainty and uncertainty correlations.
    - develop and validate novel products of value for e.g. characterising land-ocean fluxes, or ocean CO_2 fluxes over different regimes, with the associated parameters (sea state, skin temperature, ocean colour, etc...);
    - ensure full product validation through support for the development and deployment of autonomous instrumentation for areas that are inaccessible to in situ teams;
    - establish strong communication channels with the carbon cycle community at all levels including e.g. the agriculture and forestry sectors to examine terrestrial fluxes;
    - support benchmarking of terrestrial models against satellite products.
    - support the study of key missing processes through “more intimate” small-scale studies to better understand the parameterizations at the regional/global scale. This should include support to access the appropriate data products.

Recommendation B2_6: improve consistency, traceability and uncertainty characterisation of satellite data products through intercomparison and product validation.

Recommendation B2_7: support benchmarking, data assimilation and model ensemble activities incorporating satellite products.

Recommendation B2_8: strengthen communication channels between EO, in situ and model communities at all levels.

Recommendation B2_9: support studies of key missing processes at local-regional scales by provision of appropriate satellite and in situ data collections.

Breakout 3: How do we determine the magnitude of the carbon sink of a region (e.g. Europe)? – what has to be put in place to solve this open question? (leads: Michael Buchwitz, Philippe Ciais)

This discussion focuses around the discrepancy between satellite inferred and bottom-up/flux inverse model estimates with the example taken as the European terrestrial biospheric carbon sink, from the Atlantic to the Urals. Bottom-up inventory and surface flux inverse modeling give an estimate of 0.17-0.45 $GtCa^{-1}$ for the periods in the decade 2000-2010 while satellite estimates (inverse modelling based on GOSAT data) are of the order 1.0–1.3 GtC a^{-1}, 1.2–1.8 GtC a^{-1}, 1.02 ± 0.30 GtC a^{-1} (Peters et al., 2010, Peylin et al., 2013, Chevalier et al., 2014, Reuter et al. 2014). Reconciling these discrepancies requires analysis of the large differences between approaches, their associated uncertainties and dependence on ancillary information for their solution. Europe is used as the test case, but the conclusions/recommendations are applicable to all regions.

While this is an open research issue, there are many documents which summarise the state-of-the-art and outline strategies for improvement and related requirements. The focus of the discussion was thus to identify specific recommendations for high-priority actions which need to be funded.

How do we to optimally use existing satellite data to answer our question(s):
Satellite XCO2 and XCH4 retrievals have significantly improved during recent years and are increasingly being used to obtain information on sources and sinks. Nevertheless much more work is needed for satellite based inversion to clearly surpass in-situ based inversions. This not only requires additional effort for retrieval algorithm improvements but also continuous iterative improvement cycles (e.g. GHG_cci) and calibration improvements. In addition, there are (non-satellite) mandatory activities that will improve inversion of satellite observations, which require support as part of a focus on end-to-end projects, particularly:

- Key observations that improve the retrieval and/or are needed for interpretation of the satellite data (TCCON, in situ, ...);
- Improved transport models (higher resolution, evaluation);
- Improved assimilation systems merging top-down and bottom-up approaches
- Laboratory measurements (spectroscopy);
- Expansion of the number of sites in TCCON.

Recommendation B3_1: invest in continuity of priority projects and data networks e.g. end-to-end projects such as GHG-CCI, TCCON, in situ)

How do we ensure future satellites address the need to disentangle / quantify natural and anthropogenic carbon fluxes better?

The outcomes of the COP-21 Paris Agreement identify a need for assessment of net fluxes. Current satellite methods focus on natural fluxes but the impact of anthropogenic emissions and their uncertainty adversely affects these efforts. This implies improved information on anthropogenic emissions is needed for both natural flux estimation, but also for policy-related applications. While improved observing systems have been proposed and detailed studies have been conducted (e.g., CarbonSat, CarbonSat constellation, EC 2015 report on CO2) for separating natural and anthropogenic CO2 and CH4 fluxes at regional scale, there is an urgent need to take concrete steps towards implementation.

Recommendation B3_2: Implement proposals and report recommendations on observing systems for separating natural and anthropogenic CO2 and CH4 fluxes at regional scale.

At which scale can we combine top down and bottom-up measurements so that they can complement each other?
Currently the answer to this question is determined by the objectives of the assessment, the availability of observations and on key parameters such as flux distribution, atmospheric transport patterns or flux “hot spots”. If the objective is to provide a global assessment then the appropriate scale to compare top down and bottom up methods is that of large regions (e.g. RECCAP, Transcom) appears. However, over some better sampled regions (e.g. US, Europe, China) the appropriate scale may be the one of e.g. middle sized EU countries, Chinese provinces or US states with intensive CH4 extraction activities. In doing such selections emphasis should be placed on consistency between scales.

Recommendation B3_3: Identify experiments at scales of large regions and finer, ensure that these are globally coordinated and there is an emphasis on consistency and traceability of methods between regions and across scales.

Can we use recent observations to re-analyse past changes in the carbon budget of a given region?
Given that changes in the carbon cycle generally are best observed against a background of long time periods, it is very important (also for future carbon observation and analysis systems and the interpretation of their results) to understand flux differences obtained from e.g. long term in situ records and more recent satellite observations to enable consistent homogeneous time series of fluxes to be derived. Past experience shows that it is a difficult task to rescue and reprocess “historical” data (e.g. due to calibration) to increase the length of flux time series, thus every effort is needed to ensure the necessary information content in the data is preserved/maintained both for in situ and satellite data and that these data are properly archived.

Recommendation B3_4: Ensure there is an effort to maintain/preserve both in situ and satellite data records and that they are properly archived in a way that permits understanding flux differences between them and thus the generation of consistent homogenous time series of fluxes.

Do we need a follow up programme to RECCAP to regularly update regional budgets?

The RECCAP exercise produced the first regional scientific assessment of carbon budgets but it was a very large exercise to organise and in addition had relatively little contribution from satellite observations. Thus for future RECCAP-like initiatives a greater inclusion of satellite CO2 and land / ocean surface observations should be sought (e.g., by the consistent integration of available observations in data assimilation systems). In addition the organisational overhead implies that future activities could target parts of the regional budget with a specific focus on key processes, regions, gap closure and data availability. In doing so there needs to be a strong effort to ensure that research projects (funded nationally or by EU e.g. H2020), projects dedicated to exploiting and improving satellite products (JAXA, NASA, ESA) and infrastructure (e.g. NEON, ICOS, CERN, TERN) are properly coordinated towards an agreed common goal e.g. assessing the GHG balance of Europe at regional to continental scale. Such activities should also be coordinated extra-regionally e.g. US/Europe/China/Japan etc.

Recommendation B3_5: Ensure that there are updates to regional budgets and that where contributions towards RECCAP-like exercises are planned that these are coordinated within and between regions, such that a RECCAP style global assessment can be conducted.

The second group of breakouts were designed to look at the future with respect to identifying problems/priorities, satellite and in situ product requirements and the interface between models and data and projects to address in a consolidated manner. The breakouts were parallel such that the problems/priorities and model-data interface did not condition the data product discussion or vice versa. The objective of this exercise was to examine whether the different viewpoint produced common threads of requirement/discussion.

Breakout 4: The unresolved questions in the Carbon Cycle: what are the priorities and how satellite data may contribute? (leads: Dave Crisp and Mark Dowell)

The identified priorities in terms of key unresolved issues comprise - tropical forest disturbances, anthropogenic emissions, emissions and sinks of inland water and wetlands, the quantification of respiration and validation of flux inversion models. A proposed experiment to address each case is formulated below.

Tropical Forest Disturbances

Tropical forest disturbance relates in particular to the development of robust monitoring and verification systems to determine to what extent policy initiatives such as REDD and REDD+ are effective in reducing atmospheric GHGs. The objective of the exercise is to determine if there is an observable signature of a disturbed or degraded forest. the following steps are envisaged;

- Compile existing ground based and space based measurements of the Amazon (e.g., optical, lidar, microwave, atmospheric measurements), taking advantage of already reported evidence and databases in existence at e.g. INPE.
- Identify regions that have been disturbed and characterize the type and degree of disturbance, both in situ and from space.
- Compare information content of disturbance for each type of space based observation (roughness, LAI/ fapar/albedo, biomass, SIF, tree height, etc.) and the available satellite measurements.
- Where possible estimate CO2 flux change associated with disturbance and its detectability by existing/planned satellite sensors.

Recommendation B4_1: examine the potential for space-based disturbance/degradation using multiple satellite and in situ data streams

Monitoring Anthropogenic Emissions

Understanding of the attribution and quantification of patterns of carbon emissions from anthropogenic sources and reduce the growing uncertainty of anthropogenic emissions of carbon is critical for budget calculations and policy impact assessments. Here the experiment is dedicated to determining to what extent and where a robust space-based greenhouse gas observing system could improve on existing CO2 and CH4 inventories. This involves:

- Perform an Observational System Simulation Experiment (OSSE) for a multi-satellite observing system that includes:
  - Up to 3 Low Earth orbiting (LEO) satellites, with characteristics similar to those of Carbonsat

    - Up to 3 Geostationary (GEO) orbiters, stationed over Europe/Africa, North/South America, and East Asia.
    - Combinations of up to 3 GEO and 3 LEO satellites.
- Assess the ability of the system to:
    - Detect fugitive emissions from known and unknown sources - the experiment is conducted with known examples and hidden examples (training and testing).
    - Quantify emissions for individual nations, mega-cities and large industrial sources.

Recommendation B4_2: conduct OSSEs to examine satellite capabilities for anthropogenic emissions detection and monitoring alone as well as in combination with complementary societal, in-situ and EO data in a CCDAS/FFDAS framework.

Emissions and sinks of Inland Water and Wetlands
Lateral transmission of carbon and the role of lakes, rivers and wetlands as conduits are not well known. This experiment looks at the potential contribution of space based measurements to quantify and monitor CO_2 sink capability, CH_4 emissions and lateral transport of CO_2 from lakes, rivers, and wetlands to the ocean. For a well characterized river/lake/wetland the experiment examines the types of ground based and space based measurements that must be combined to:

- Identify and characterize the areal extent and type of watershed
- Areal extent, water level and changes over time, and discharge rates

Given these products the experiment then seeks to:

- Quantify pCO_2 of water and its changes over time
- Quantify CH_4 emissions, and changes over time

Finally, an OSSE is conducted to:

- assess the detectability of changes recorded by space based and ground based observations as identified above. These include evaluation of high resolution imaging, multi/hyperspectral, passive and active microwave, active altimetry, scatterometry, and atmospheric sensors.

Recommendation B4_3: assess the contribution of satellite observations in combination with in situ monitoring to assess lateral transmission of carbon from lakes, rivers and wetlands.

Quantifying Respiration
While estimates of GPP can be made from space, the critical parameter is NPP, for which knowledge of the respiration is required. Thus the objective is to examine if space based measurements can directly quantify respiration or alternatively changes in respiration associated with climate change. This involves constructing an OSSE to

define the requirements of space-based active and passive CO_2 sensors for quantifying respiration. The experiment proceeds by:

- performance of a high resolution "Nature Run" that resolves the diurnal and seasonal behaviour of the land biosphere and hence traces uptake by photosynthesis emissions from respiration. This can be used to identify and discriminate the spatial (including vertical) signatures of respiration (or its correlated/anti-correlated species)
- given this knowledge design an active or passive observing system that has the horizontal, vertical, and temporal coverage and resolution needed to directly detect respiration (or its proxies).

Recommendation B4_4: conduct an OSSE to examine using active and passive CO_2 sensors to see if the signal of respiration or respiration change can be identified.

Validating Inversion Models

A critical issue with flux inversions is validation. Currently these flux inversion models are validated by comparing the retrieved GHG distribution to "excluded observations" of the GHG field. However, it would be better if it is possible to validate greenhouse gas flux inversion models against actual measured fluxes from flux towers. The experiment involves determining the conditions under which data from individual flux towers of mesoscale arrays of towers can be up-scaled for use in validating local, regional, or global flux inversion results. The experiment comprises:

- Performance of a high resolution nature run to assess the meteorological conditions and source/sink configuration (distribution, uniformity, strength) for which local fluxes are representative of the larger, policy-relevant areas represented in flux inversion models.
- Review of existing flux tower data to determine the conditions under which the measured fluxes appear to be sufficiently uniform to be up-scaled to domains as large as "policy relevant areas" simulated by flux inversion models

An alternative approach to up-scaling flux measurements based on suitable conditions, would be to use a process model in a data assimilation framework, i.e. assimilate the flux measurements .

Recommendation B4_5: develop an experiment to determine the conditions under which flux inversion models can be validated against actual measured fluxes from flux towers.

Breakout 5: Novel Observations and Products for 2021 and beyond: new and better exploitation of satellite and in situ data (leads: Hartmut Boesch, Shaun Quegan, Shubha Sathyendranath)

There exists a need for an improved interface between space-based observations, ground data and models, and there is limited understanding of some processes. To tackle these issues requires consideration of the observations and products needed from the perspective of existing satellite and in situ data and new potential products for the near term. The discussion in the break out produced recommendations for each domain (land, ocean and atmosphere) and for cross-domain issues:

Land:

- For measuring land surface change particularly for identifying/monitoring tropical plantations & secondary forests:

Recommendation B5_1: provide Sentinel 1 data in geocoded form (not done at present)
Recommendation B5_2: provide PALSAR L-band data to accompany Sentinel-1 data for plantation and secondary forest identification.
Recommendation B5_3: design/establish a system for pan-tropical forest monitoring with Sentinel-1, PALSAR-2 and Sentinel-2/Landsat data aimed particularly at helping to quantify the Land Use Change Flux and mapping plantations/secondary forests.

- In support of biomass determination:

Recommendation B5_4: Provide a central node for combining Terrestrial Laser Scanner measurements being made by several groups.
Recommendation B5_5: Explore the potential for L-band radiometry (Vegetation Optical depth, Vegetation Water Content) for biomass/vegetation moisture.

- Other products require investigation for the carbon cycle in particular Land Surface Temperature.

Recommendation B5_6: Revisit the value of Land Surface Temperature for Carbon cycle calculations

Ocean:

- Pools and fluxes of carbon in the ocean:

Recommendation B5_7: develop phytoplankton carbon, total and components by type and carbon-to-chlorophyll ratio products
Recommendation B5_8: exploit functional dependence on light, temperature, community structure to generate photosynthesis parameters from space.

Recommendation B5_9: develop methods for converting primary production into export production.
Recommendation B5_10: explore methods for estimating inorganic carbon components and indicators of ocean acidification.
Recommendation B5_11: use relationship to the coloured components to estimate dissolved organic matter.

- At the interfaces:

Recommendation B5_12: produce photosynthetically available radiation at the sea surface and primary production ensuring they are consistent and harmonised with land. This should include exploration of the value of FLEX observations**.**
Recommendation B5_13: explore the consistency of fCO_2 at the sea surface with flux estimates over land.
Recommendation B5_14: generate carbon fluxes from land into the ocean.

Atmosphere:

Atmospheric CO2 observations provide an important top-down constraint on regional surface fluxes but there is a need to account better for aerosols in their generation particularly to improve historical satellite CO_2 datasets.

Recommendation B5_15: improve current and historical satellite CO2 datasets, especially to better account for aerosols.
Recommendation B5_16: include consideration of aerosol in the development of future CO2 missions.
Recommendation B5_17: explore the use/benefit of other tracers to ocean-atmosphere or land-atmosphere fluxes: CO, OCS, DMS, SIF.
Recommendation B5_18: explore horizon scanning for technologies that would allow isotope measurements from space.
Recommendation B5_19: explore the synergy of products from active sensors (Merlin for CH4) with those from passive sensors.
Recommendation B5_20: improve model transport processes and access to weather data.

Cross-cutting issues:

As a European contribution to carbon cycle studies there is a need for continuation and adaptation of the work on algorithms, validation, error characterization and models after the end of the ESA CCI, in particular:

Recommendation B5_21: ensure continuity in existing parameters of importance for the carbon cycle by adapting ESA Climate Change Initiative products to a carbon perspective, extending them with Sentinels and other upcoming sensors and ensuring records are brought as up to data as possible.

Recommendation B5_22: Consider an ESA Carbon Initiative to develop downstream carbon specific parameters not currently in ESA CCI e.g. atmosphere-ocean gas fluxes.

More generically and globally the following issues need attention:

Recommendation B5_23: Identify ground-based and airborne datasets (e.g. lidar) datasets which are often stored at many diverse locations are difficult to access and make them consistent, traceable and collectively available;

Recommendation B5_24: Provide support for ground-based product validation and in situ networks as they provide critical anchor points for long-term carbon/climate records from space and ensure these data are appropriate for validation through data mining, new campaigns and better interfaces with non-space observing bodies, networks and cruise teams.

Recommendation B5_25: Compare and improve algorithms with an emphasis on global representativeness, multiple sensor portability and rigorous uncertainty characterization (cf CCI).

Breakout 6: New Frontiers for models and observations: What can we imagine and what projects can be designed - targeted RECCAPs, CxMIP exercises, integrated carbon observing systems? (leads: Pierre Friedlingstein, Julia Marshall)

Strengthening the interface between models and observations is vital for improved understanding, modelling and subsequently prediction of the impact of climate on the carbon cycle and vice versa. This requires that the observation and modelling communities have to communicate better and move towards consistency in definition of variables, understanding of assumptions and specification of terms. in addition, the provision of data in common formats is vital to ensure uptake in the model community. Moves have been made to develop common data formats e.g. CCI using NetCDF-CF formats for all products and the efforts of Obs4MIPs to gather data consistently into one place for use in model intercomparison exercises generically. These efforts need continuing and strengthening.

Recommendation B6_1. Strengthen efforts to establish common data standards introduced by, for example, Obs4MIPs to allow for improved communication between groups.
Recommendation B6_2. Improve and extend data collections in Obs4MIPs and increase uptake by the carbon modeling community of these products, for example by facilitating the development of observation operators. Contributions to this from ESA include Felyx (http://hrdds.ifremer.fr), CCI (all CCI data is being organised for Obs4MIPs) and Coupled Atmosphere Biosphere Virtual Laboratory (http://earthsystemdatacube.net/).

As well as improving interfaces at data and community level there are priority areas that require exploring. These include:

- understanding lateral fluxes
- description of marine ecosystems
- introduction of trait-based instead of plant-function type (PFT) descriptions in ES models.
- top-down flux estimation informed by new products
- model development to constrain emissions in Europe

Understanding lateral fluxes (land-freshwater, ocean)
As mentioned above a key missing component of carbon cycle models is consideration of the transfer of fluxes from land to ocean. It is suggested that three projects should be designed to address this issue - one focusing specifically on rivers and carbon, one concentrated on erosion along Arctic coasts as a critical carbon contribution through loss of permafrost sediments in storms and finally a focus on improving consistency in budgeting across domains (land, ocean, atmosphere).

Recommendation B6_3. conduct an intensive (in situ+) riverine study on carbon transport to ocean.

Recommendation B6_4. provide coordinated, consistent products from Earth observation in support of and as a contribution to the Arctic coastal erosion assessments (e.g. see http://www.arcticcoasts.org)
Recommendation B6_5. provide support for activities dedicated to improving the consistency of regional budgets for carbon with an emphasis on cross-domain consistency.

Representation of marine ecosystems
The ocean is carbon terms is primarily considered from the perspective of air-sea exchange via the solubility pump, with less consideration of marine ecosystems, which act to produce and sequester (by particulate sinking) carbon, but are also vital in terms of the food chain. Recent efforts have been dedicated to the development of Dynamic Green Ocean Models to understand the role of the carbon cycle more holistically (see MAREMIP). However, the outputs of DGOMs are difficult to interpret because of the lack of appropriate observations for evaluation. Satellite data provide information on ocean colour (see OC_cci) but there is the prospect for ecosystem composition in terms of differentiating phytoplankton and zooplankton types in support of global efforts to characterise Plankton Functional Types in the in situ MARine Ecosytem DATa (MAREDAT) effort to produce a World Ocean Atlas of Plankton Functional Types. Other key products are also needed e.g. information on Dissolved Organic Carbon (DOC). The evolution of longer data records subsequently raises the prospect of investigating ocean use change.

Recommendation B6_6. support the MAREMIP intercomparison of DGOMs through provision of ecosystem composition products from space aligned with the in situ atlas (MAREDAT).
Recommendation B6_7. explore possibilities to derived DOC from space with the objective to resolve inconsistencies between in situ measurements and theoretical framework
Recommendation B6_8. once satellite data records are long enough to permit trend analysis, initiate investigations on ocean use change (especially the foodweb - phytoplankton distributions, fisheries etc).

Shift from functional types to trait-based modelling
The observation that plant functional types, while good for carbon modelling, have difficulty in representing spatial and temporal variability of, in particular, terrestrial vegetation has initiated investigation of alternative representations based on plant traits rather than functions. This allied with the difficulty to encapsulate plant functional types consistently from satellite data raises questions about whether trait-based concepts are more compatible with satellite observations but also better able to describe land and marine ecosystems.

Recommendation B6_9. Conduct an analysis on the capacity of trait-based representation rather than functional based representation of ecosystems to describe land and marine ecosystems and their acclimation. As part of this exercise examine the compatibility of these representations with satellite observations.

Analysis of complementary remote sensing products for top-down analysis
Flux inversions rely principally on atmospheric products from satellites but efforts at attribution of sources and sinks would strongly benefit from constraints provided from satellite observations of the surface. The difficult issue with this is to ensure compatibility and consistency of products complete with uncertainty characterisation (see examples from CCI) as well as developing a consistent modelling framework that permits the integration of atmospheric and surface datasets and hence the generation of key constraint experiments e.g. XCO_2 combined with soil moisture, biomass and solar induced fluorescence, XCH_4 with soil moisture, wetland dynamics and fire.

Recommendation B6_10. Design a consistent modelling framework cross-domain to allow integration of satellite data from atmosphere and both surface domains to examine the impact of surface constraints on flux inversions.

Model development for the constraint of emissions
The current state of model development remains in the scientific understanding of natural processes domain and there is a concerted need to move to include anthropogenic processes, in particular emissions calculations to allow effective regional and finer scale budgeting and hence relevance to policy-makers. This applies equally to top-down and bottom-up schemes.

Recommendation B6_11. Improve the integration and exploitation of both satellite and in situ observations e.g. from the ICOS, TERN or NEON networks in models to examine emissions. The initial focus should be on Europe given the availability of appropriate data products and the current disagreement between inversions based on in situ and satellite sources.
Recommendation B6_12. Support model development to account for fossil fuel emissions, focusing in particular on the need to represent fine spatiotemporal properties of anthropogenic fluxes as well as the coupling with the land/ocean/atmosphere system.

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