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Operational Global Carbon Observing System

Rapports

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Final Report Summary - GEOCARBON (Operational Global Carbon Observing System)

Executive Summary:
GEOCARBON has been a big project in terms of: number of partners (including two from other two continents than Europe), global scope, geographical coverage (with case studies in the Tropics), different data and observations (from different domains), different methods and approaches (data driven, models, etc.), different monitoring platforms (in situ, satellite, airborne), different disciplines (from biogeochemical cycles to economy) and different kind of activities (from research to outreach and policy linkages). Therefore it is not easy to synthesize the main results in a 1-page executive summary.
Among the most evident results is the annual global carbon budget, provided as a joint effort between the Global Carbon Project (GCP) and GEOCARBON. The last update released in late 2014 (Le Quéré et al., 2014) showed that anthropogenic CO_2 emissions increased by 2.3% in 2013, leading to a CO_2 concentration of 395.31 ± 0.10 ppm averaged over 2013. The total anthropogenic emissions (fossil fuel, cement and land use change) were 10.8±0.5 GtC, more than 60% above 1990 emissions (the Kyoto Protocol reference year). In 2013, the ocean and land carbon sinks respectively removed 27% and 23% of total CO_2 leaving 50% of emissions into the atmosphere. These results (that are just a minor part of the overall) show the importance the ocean and terrestrial ecosystems in buffering the GHG emissions, but despite that it is also evident the continuously increasing emissions trend.
These results are based on the combination of a range of data, algorithms, statistics and model estimates and their interpretation. The integrated approach used by GEOCARBON disentangled many different components of the global carbon cycle, providing many other pieces of information to derive the whole picture. For instance, as a counterpart of the Global Carbon Budget, a global scale bottom-up synthesis of carbon cycle observations was derived by a combination of purely data-driven estimates of terrestrial and aquatic carbon fluxes at high spatial resolution for a recent decade. Although this budget cannot be closed at the global scale, for the first time, global maps of the most important carbon fluxes, which are all directly derived from observations were provided.
GEOCARBON also addressed more in details some specific aspects of the global carbon cycle, like CH_4 (in addition to CO_2) and the role of tropical areas, two key elements not fully studies to date and that are limiting our understanding. CH_4 emissions were better represented at global level, with a reduced uncertainty, particularly from natural wetlands, i.e. the largest individual CH_4 source. For the first time the global methane budget and trends was published (Kirschke, et al., 2013). The study on the tropics showed

that tropical forests, even though they potentially are carbon sinks, can become a net source of carbon; part of this work was published in Nature (Gatti et al., 2014) and showed that during dry years the Amazon basin is a carbon source of around 0.5 GtC. Many of these results were possible thank to the improved carbon cycle data assimilation systems developed indeed by GEOCARBON.
Finally a specific component of the project was dedicated to the quantification of the costs/benefits ratio of installing an improved carbon observation system and obtaining more reliable information. The results from a couple of examples only, showed that this benefit is already so large that it does justify the investment into an improved monitoring and analysis system.
Considering also its work on the requirements for an effective carbon monitoring system and the network design, GEOCARBON has been contributing, on the whole, to fill in the gaps toward the establishment of an operational integrated global carbon observing and analysis system, affecting different processes and systems and meeting the needs of a wide range of users, ranging from the research community, monitoring networks, decision makers, and others.
We believe the GEOCARBON legacy is not temporary; what we have developed (in terms of new data, information, products, system requirements, performance for network design, cost-benefit analysis, networking and liaising with the relevant community, etc.) will further impact climate policy and be exploited in the next years, particularly thank the continuing active involvement of the GEOCARBON community in the GEO work plan.
Project Context and Objectives:
Because of the anthropogenic emissions the concentration of CO2 in the atmosphere has increased by 40%, from around 280 ppm in the pre-industrial age (i.e. before 1750) to the current level of around 400 ppm. This is one of the major causes of the greenhouse effect that is affecting the global climate system. Fortunately only less than an half of the carbon emitted by humans is accumulating as CO2 in the atmosphere, while the remainder is taken up by the ocean and the land biosphere, 27 and 28% respectively in the period 2002-2011 (Le Quéré et al. 2012). In that decade the total anthropogenic emissions were 9.3±0.5 PgCy-1 (of which 8.3±0.4 PgCy-1 from fossil fuel burning and cement production, and 1.0±0.5 PgCy-1 from land use, land use change and forestry), while the removals by the ocean and land sinks were 2.5±0.5 PgCy-1 and 2.6±0.8 PgCy-1 respectively, leading to an atmospheric growth of 4.3±0.1 PgCy-1 (Le Quéré et al. 2012). In the same period the average growth rate of emissions was 3.1% per year. In 2012 total emissions have been almost 60% above the 1990 baseline, making trivial the Kyoto Protocol’s target to cut 5,2% of the Annex I countries’ emissions by then! This growing trend tracks scenarios that lead to the highest increase of the global average temperature, much above the “recommended” 2°C since the pre-industrial period (Peters et al. 2012). Timely and significant emission reductions (around 3% per year), sustained by long-term political commitment to global mitigation, would be needed by 2020 to try to keep global warming below 2 °C (Van Vliet et al. 2012). Moreover, the growth rates of CO2 concentration in the atmosphere have relied up to now on the “discount” effect by the ocean and land natural sinks, while it is highly uncertain how they will behave in the future global change scenario. Increased greenhouse gas (GHG) emissions and continued climate change may reduce the sinks’ strength or even cause carbon losses from oceans and/or natural ecosystems, acting as positive feedbacks on climate change (Ciais et al. 2012). These feedbacks could become dramatically intense if they pass a “tipping point” (Lenton M. 2011). Further delay in reducing the current emissions will lead to higher mitigation rates and costs and increase the risk to cross tipping points; the target of remaining below 2 °C may thus become unfeasible.

Therefore it is fundamental to improve our capacity to monitor these changes and predict future trends, in order to i) better understand the processes, dynamics and drivers (both natural and anthropic) controlling the coupled carbon-climate system, and its variability and change, and ii) support the climate policies for mitigation and adaptation. Systematic, consistent and traceable data, information and tools on carbon sources and sinks, and the related economic scenarios, are needed by decision makers to timely address mitigation and adaptation policies and to respect their commitments of GHG emissions' reduction. Reliable measurements are indeed necessary to support national and regional programs for emissions reduction or increased sequestration, necessary to meet the objectives of the international agreements.

To date, efforts to monitor and report carbon emissions and certify carbon credits have been based mostly on self-reported (by countries) data derived by local inventories, statistics, emission factors, etc., rather than independent observations. However their high uncertainty limits their ability to effectively verify the progress of GHG management strategies. Past and current observations mostly derive from limited, short term and discontinuous research efforts, with a spatio-temporal resolution not adequate enough for the emerging needs. Despite there are numerous networks monitoring C-cycle, many different approaches to measure C-cycle, and an impressive wealth of scientific information, there is also high uncertainty on the numbers provided, a lack of continuity and sustainability, many under-represented regions and ecosystems types, and the interoperability of the systems and intercomparison of the results are difficult as well it is difficult to translate science into policy relevant information.

Therefore now more than ever we need an increasing quantity and improved quality of observation-based carbon data and products, and this is possible only if an operational global carbon observing and analysis system is established. In this context was conceived the project GEOCARBON, with the main objective to provide coordination to the global efforts for monitoring carbon cycle in the frame of GEO toward the establishment of an operational global carbon observing system.
Specific objectives of the project were:
• Provide an aggregated set of harmonized global carbon data information (integrating the land, ocean, atmosphere and human dimension) based upon existing observations and complemented by new ones.
• Develop and improve different Carbon Cycle Data Assimilation System (CCDAS).
• Define the specifications for an operational Global Carbon Observing System.
• Provide improved regional carbon budgets of Amazon and tropical Africa.
• Provide comprehensive and synthetic information on the annual sources and sinks of CO_2 for the globe and for large ocean and land regions of the world (global carbon budget).
• Improve the quantification of global methane sources and sinks and their variability and develop the observing system component for methane.
• Provide an economic assessment of the value of an enhanced Global Carbon Observing System.
• Strengthen the effectiveness of the European (and global) Carbon Community participation in the GEO system.

These objectives were achieved through the following 8 complementary project's components (CMPs, see also figure 1): CMP1 – Collecting, harmonizing and synthesizing global carbon observations; CMP2 – Integrating these observations into improved carbon cycle data assimilation systems; CMP3 – Requirements for an integrated global carbon observing system; CMP4 – Tropical component (Amazon and Africa) of the global observatory; CMP5 – Global carbon budgets and their uncertainty; CMP6 –

Methane; CMP7 – Economic implications; CMP8 – Dissemination and link with GEO.
Project Results:
Global land stocks and stocks changes (WP1)
In WP1 existing observations and data were integrated and optimized to provide best available datasets with global information on land stocks and key changes related to land cover, fire, harvest, forest age and forest biomass. The approach consisted on integrating in-situ networks, inventories and remote sensing approaches to evaluate and integrate existing large areas datasets, and to improve and fill gaps using fine-scale or more regional/local studies where needed. A number of global datasets were produced, employing data derived in previous and running projects and built upon requirements and efforts by international observing networks (i.e. IGCO, GOFC-GOLD) and international processes such as GEO.
Among the main outcomes of this WP are:
- the production of a forest-age distribution dataset representing for the first time the global-scale structure of forests (figure 2): global datasets of cropland and forest harvest statistics and forest age distributions were developed and processed to a standardized and documented data format. Cropland harvest statistics for 175 crops were developed from country-level reporting in the ca. 2000 period from varying scales of political reporting units. Three wood harvest data products were developed: the first from 2004 FAOSTAT data, the second by acquiring sub-country level statistics from forest management units or from the FAO FRA statistics, and the third by applying a new downscaling method to constrain wood harvest to forested areas. The global forest age distribution dataset was produced by acquiring forest inventory data from 2000-2010 for 60 countries. Forest age was estimated from aboveground biomass in mixed-age tropical forests. The consistency of the global forest age distributions was compared with existing global datasets on burned area, tree heights and independent estimates of biomass, and regional secondary forest distributions (Brazil).
- the creation of aboveground biomass for forest areas mapped globally at 1 km resolution with improved accuracy for the reference period of circa 2005 – 2010 (figure 3): given the diversity of available data and vegetation characteristics, the dataset was derived using a regional approach, applying specific methodologies for the boreal and tropical components. Vegetation biomass north of 10°N latitude was estimated from multi-temporal Envisat Advanced Synthetic Aperture Radar (ASAR) images using the BIOMASAR retrieval algorithm, and validated against inventory data (where available) and verified against other datasets of proven quality. Forest biomass for tropical areas was derived by integrating two existing pan-tropical biomass maps using a fusion approach specifically developed for this task, which uses the complementary information of different maps in combination with local reference data. A large effort was undertaken to compile and harmonize the reference dataset, consisting of a variety of high-quality local biomass data distributed throughout the tropical belt, also used for validation purposes.
Moreover the validation of a number of global land cover datasets proved that the ESA's Land Cover Climate Change Initiative (LC-CCI) product achieves the best results for forest areas. Finally the analysis of three global emission inventories showed good agreement on biomass burning hotspots and observed seasonality, and allowed to explain regional differences.

Global land biosphere-atmosphere fluxes (WP2)
WP2 contributed to several aspects needed to maximize the information gain from in-situ data thought upscaling. Upscaling is the art of "learning" (i.e. optimizing the predictive capacity of an empirical data-adaptive algorithm) some biophysical or biogeochemical responses to environmental drivers from these in-situ observations and then applying the resulting algorithm to predict global patterns of the variable of

interest.
Particularly during the GEOCARBON lifetime WP2 produced a new harmonized global eddy covariance data set: the global eddy covariance data collection was extended with an approximately doubling of the the data points. Chronically under-sampled regions received specific attention i.e.: >20 new site-years from Asia were added (from 8 towers); 40 new site-years from Australia were added (from 10 towers); >20 new site-years from Africa were added (cf. CarboAfrica project); 6 new site-yeas from South America were added (3 sites); the dense networks from Europe and the US were further complemented substantially. A new processing scheme for carbon fluxes was developed and implemented in agreement with AmeriFlux and ICOS. The processing scheme allows for an accurate QA/QC processing across sites as illustrated in the figure 4. The collection of the measurements, the extensive QAQC applied and the exchange with the data owners to solve all the issues has been a huge work, underestimated at the beginning of the project. The quality of the results is now for sure a big advancement respect the previous version of the synthesis dataset.
Another key result is the emerging of the FLUXCOM initiative that brings together scientists with expertise in different state-of-the-art machine learning methods and carbon cycle research. The expert teams implemented all of these methods at the MPI-BGC aiming at minimizing potential sources of inconsistencies by guaranteeing the following properties: implementation on the same high-performance computers, receiving the same training data, being evaluated with a consistent cross-validation scheme. This systematic setup provides a new generation upscaling environment that minimizes the influence of the preferences of individual researchers and leads to a highly objective approach to the problem. Two main approaches to upscaling were pursuit:
1. A climate driven long-term, but coarsely spatially resolved upscaling was performed (0.5° spatial resolution; period 1982-2011).
2. A high resolution, exclusively remote-sensing driven upscaling was performed – but covering a much smaller temporal period (0.083° spatial resolution; period 2000-2012) (figure 5).
In both approaches an ensemble of global spatially explicit estimates of gross primary production (GPP), ecosystem respiration (RECO), and net ecosystem exchange (NEE) anomalies was produced. A full factorial set-up allows for quantifying different sources of uncertainties.
A specific result was that global patterns of NEE anomalies (derived from the first approach: Upscaling with climate drivers) reveals a strong consistency in terms of interannual-variability with the “residual land sink” (inferred primarily from atmospheric carbon dioxide concentrations). This consistency can be considered as a major step forward compared to earlier efforts aiming at upscaling NEE.

Lateral carbon fluxes (WP3)
The work performed in this WP led to a better conceptual representation and quantification of the carbon fluxes at the boundary between the continents and the oceans.
Firstly the global MARCATS/COSCATs segmentation (Laruelle et al., 2013) was produced. This is the first of its kind to systematically and consistently integrate the entire land-ocean aquatic continuum. It also provides several inter-comparable segmentation layers ranging from the individual watershed to the large scale regional aggregation. This work allowed producing new high resolution estimates of the volumes and surface areas of the different compartments of the LOAC and was used as canvas for a detailed carbon budget of the Northest US coast (Laruelle et al., 2014a).
Secondly, for each region of the MARCATS/COSCAT segmentation, lateral carbon fluxes at the land-ocean boundary were derived from existing spatially explicit estimates produced by global empirical

models calibrated on field measurements. These models simulate riverine export of carbon and nutrient at a 0.5° resolution. The fluxes for each region were obtained by aggregating all watershed comprised within the studied geographic unit.
A new estimate of the global CO2 outgassing from rivers was also produced using sophisticated statistical analysis and exploiting a worldwide database of CO2 partial pressure (pCO2) data collected at 1182 sampling locations (figure 6). This flux has long been overlooked in the global carbon budget and is still associated to large uncertainties (Regnier et al., 2013). Our new estimate for the global CO2 evasion is 650 (483-846) Tg C yr-1, which is more conservative than a first regionalized estimate of 1800 Tg C yr-1 suggested by Raymond et al. (2013). This difference is mainly due to lower tropical pCO2 estimates in the refined study. Our maps reveal strong latitudinal gradients in pCO2, the surface area of the riverine network and FCO2. Our calculations reveal that the zone between 10°N and 10°S contributes about half of the global CO2 evasion.
Then, an updated regionalized global estimated for the CO2 outgassing from estuaries was extrapolated from an extensive compilation of local studies (Laruelle et al., 2013; figure 7). Over 160 published estimates of annually averaged CO2 emission rates in estuarine environments were gathered and assigned to 45 regions (MARCATS). A global estuarine typology (Dürr et al., 2011) was used to sort the data and produce type specific CO2 emission rates in 40% of the regions. In the remainder of the world, global type-dependent average rates were used. The updated budget yields a CO2 flux of 0.15 Pg C yr-1 towards the atmosphere, somewhat lower, but still within the uncertainty interval of previous global budgets (0.25 ± 0.25 Pg C yr-1, Laruelle et al., 2010, Cai et al., 2011).
Finally a new global budget for CO2 outgassing from continental shelf seas was developed in using 3 million pCO2 measurements extracted from the SOCAT database as well as a suite of spatial en temporal integration methods depending on the data density. The approach also accounts for ice cover, which inhibits the gas exchanges. The calculations predict a global CO2 sink estimate of 0.19 ± 0.05 Pg C yr-1 (Laruelle et al., 2014b, figure 8), which falls in the low end of previous estimates. Reported to an ice-free surface area of 22 106 km2, this value yields a flux density of 0.7mol C m-2 yr-1, ~40% more intense than that of the open ocean. The regionalization of our calculations allows identifying regional patterns and, in particular, the significant contribution of Arctic shelves to the global coastal CO2 uptake (0.07 Pg C yr-1).

Ocean CO2 fluxes (WP4)
Over the course of the project, WP4 has made exceptional progress toward the quantification of the global ocean carbon sink, especially with regard to its temporal and spatial variability. This progress rests on two major pillars. First, the protocols and procedures for collecting and harmonizing the observations of the surface ocean pCO2 have been developed further and improved through the Surface Ocean CO2 Atlas (SOCAT) efforts. This has resulted in the hitherto largest data-base of quality controlled pCO2 observations with more than 10 mio observations covering all ocean basins (Bakker et al. 2014). The second major achievement is the development of a novel extrapolation method based on neural network methodologies (Landschützer et al. 2013) that has permitted these researchers to map out the observations to a global monthly grid at 1x1° resolution, covering the period 1982 through 2012 (Landschützer et al. 2014, figure 9).
The spatial distribution of the neural-network-based pCO2 and air-sea CO2 fluxes confirm the large-scale features identified in the Takashashi climatologies with strong supersaturations in the equatorial Pacific and annual mean undersaturations in the mid-latitudes and especially in the North Atlantic (Figure 9). The new, more finely resolved pCO2 and flux estimates reveal, however, many finer-scale structures that were

previously missed in the Takahashi climatologies due to its coarse grid (5x5 degrees). A good example is the outgassing off central America associated with the upwelling induced by the gap winds.
The new product now adds the temporal dimension to the air-sea CO2 fluxes, thus permitting researchers to investigate the variability of the global carbon sink at monthly resolution over three decades. Figure 10 reveals that this new observation-based product suggests a substantial amount of decadal variability in the global ocean carbon sink, while none of the models shows such variability. This suggests that the current generation of ocean carbon cycle models may be missing an important element of variability. The substantial amount of decadal variability is also evident in the CO2 flux product of Rödenbeck et al. (2014), although masked also by a higher degree of interannual variability which is mostly absent in the neural network based estimate of Landschützer et al. (2014).

Anthropogenic emissions and trade fluxes (WP5)
WP5 compared the following several fossil fuel products in terms of spatial and temporal distribution of CO2 emissions:
• "IER-EDGAR" product derived in the CARBONES European project, based on EDGAR spatial flux distribution with specific temporal profiles per emission sector. The IER institute (http://www.ier.uni-stuttgart.de/) provided 3-hourly resolution emissions (considered as our reference product).
• "CDIAC-Andres" monthly mean product produced by CDIAC center, version V2010; http://cdiac.ornl.gov/epubs/fossil_fuel_CO2_emissions_gridded_monthly_v2010.html
• "CTRACKER" product derived at NOAA-CMDL for the CarbonTracker atmospheric inversion; http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2013_doc.html#tth_sEc6.1
• "ODIAC" product derived from CDIAC national emission and in situ and nightlight statistics for the spatial discretization (Oda et al. 2011),
• "PKU" product constructed at the University of Beijing; based on sub-national fuel consumption data for up to 64 fuels and 7 sectors (PKU-FUEL).
• "FFDAS" product derived from a fossil fuel data assimilation system; http://hpcg.purdue.edu/FFDAS/
Differences between the six products can be used to estimate the uncertainty associated to the spatial distribution of fossil fuel emissions. However, some cautions should be taken and the spatial differences do not represent the "true" fossil fuel emission uncertainty, given that the selected products do not necessarily include the same emission sectors. For instance, some include "waste burning" or "biofuel" and others do not. It is thus difficult for non-specialists to decipher between "true" uncertainty and what we could refer as "apparent" uncertainty due to differences in the product definition. For climate users and carbon cycle modelers, these subtleties are often neglected and sources of "apparent" uncertainties.
With theses caveat in mind, although most product use the same national statistics, the differences in the spatial and temporal distributions are significant and linked to:
• the spatial resolution at which the product is created which impacts for instance the extent of "urban" versus "rural" areas and thus the fine scale flux distribution;
• choices made to distribute in space the country total fluxes for different emission sectors: from a simple approach following population density to more complex approaches mixing population density, power plant location, night light intensity,…, depending on the sector.
• choices for the temporal profile applied to the annual mean emission, from standard profile constant everywhere to more complex profiles varying with emission sector and climate.
Overall, the spatial differences should be discussed and evaluated as a function of the spatial scale that is considered (given that similar national emission statistics are used for most products). For example, at

high resolution the PKU product has lower emission than IER-EDGAR for rural areas (i.e. countryside pixels with low emission rate), while this is the reverse for urban areas (i.e large industrial cities with high emission rates). The differences smooth out at lower resolution (i.e above 2°) especially for the high emission areas and become much smaller.
Figure 11 displays the spatial distribution of the annual fossil fuel emissions for a particular year (2007) of IER-EDGAR. Figure 12 shows the temporal distributions of the emissions.

Atmospheric and other constraining data sets (WP6)
The main outcomes of this WP are:
- the creation of an updated Global Soil Organic Carbon stock database at 30 arc-second (baseline 2010), see figures 13 and 14. The soil organic carbon stock database was largely incremented compared to the previous versions of the database, with the addition of about 8'000 georeferenced soil profiles, covering the African continent, where there was a lack of information. The final global database, contains a set of nearly 24'000 georeferenced soil profiles derived from many sources, and report the SOC stock associated to each single profile for two reference depths: 0-30 and 30-100 cm. The database was created using existing available global datasets such the Harmonized World Soil Database, FAO Global Land Cover Share database and other soil carbon datasets and profiles. The final product and the methodology is published through FAO GeoNetwork www.fao.org/geonetwork
- the creation of two FAPAR time-series: the first data set covers the period 1982-2011 and has served for instance the detection of extreme anomalies in vegetation productivity as reported by Zscheischler et al. (2013, 2014, see also figure 15). The second data set was created, where FAPAR was tiled according to vegetation types allowing for data driven estimates of e.g. interannual variability as stratified according to vegetation type (Del. 6.1). Some first analysis in on this very aspect revealed that global spatial patterns of inter-annual variability are very specific to certain vegetation types, indicating that ecosystem-intrinsic controls may partly overwrite large-scale environmental controls. Based on this task, we also developed and novel 3D gap-filling algorithms to pre-process these highly fragmented spatiotemporal data set (von Buttlar et al. 2014). The method has proven to be specifically powerful in the presence of large periodic gaps as they frequently occur in the high latitudes in the case of satellite remote sensing data.
- the provision of a synthesis of the recent state of the art atmospheric inversion results (figure 16). The mean annual flux, long-term trend and inter-annual flux variations (IAV) have been analysed and compared under the Global Carbon Project web site (CATLAS: http://www.globalcarbonatlas.org) as well as a specific site that includes other estimates from GEOCARBON systems:
http://transcom.globalcarbonatlas.org Major findings are:
• most inversions agree on the inter-annual variations of the land and ocean fluxes, largely controlled by El-nino events over the Tropics. They also agree on the land/ocean partitioning, but this is most likely due to the prior information used for the ocean;
• transport errors (differing between models) and lack of atmospheric constraint make the tropical fluxes highly uncertain;
• the largest total land sink in the Northern Hemisphere is nearly unanimously located in Eurasia (predominantly in the boreal zone), while the largest uptake rates per unit area are found over Europe (41±41gC/m2/yr) versus 33±22 gC/m2/yr for North America and 27±11gC/m2/yr for North Eurasia. North America and Europe are robustly identified as land sinks of a magnitude that could exceed 30 % of their fossil fuel emissions;
• uncreasing trends in carbon uptake over the period 1995–2010 are nearly unanimously placed in the

terrestrial biosphere (assuming fossil trends are correct), with around 0.5 PgC/yr more uptakes in the northern land after 2003 than during the period 1995 to 2003;
• there is no clear agreement in terms of regional CO2 fluxes which thus suggests that the primary constraint brought by atmospheric inversions is at continental/latitudinal scale.

Cross-WP integration and synthesis (WP7)
The WP7 produced three major results:
Firstly, a data sharing platform that enables carbon-cycle researchers to access and share a wide range of observations. The data-sharing platform (http://www.bgc-jena.mpg.de/geodb/geocarbon/Home.php) is hosting 31 GEOCARBON data products by today that could be made available to the user community. The idea and key innovation is that a data provider keeps full control of a submitted data set and can upload new versions of the data set at any time. Hence, the user community can be contacted and informed about major updates or potential errors. The idea is that the user “subscribes” to a data set and receives news and updates if necessary. The archive is growing over time; we registered almost one download/day over the project duration and have implemented an infrastructure that ensures that the GEOCARBON portal is visible to and searchable via GEO.
Secondly, a global scale bottom-up synthesis of carbon cycle observations. Constraining carbon fluxes between the Earth's surface and the atmosphere at regional scale by observations is essential for understanding the Earth's carbon budget, identifying data gaps, and predicting future atmospheric carbon concentrations. Previous carbon budgets have mostly been derived at global and continental scale, and often rely on process-based models without taking into account that these models might not have been developed independently leading to correlated model estimates or biases in the budget. We combined purely data-driven estimates of terrestrial and aquatic carbon fluxes at high spatial resolution for a recent decade. The idea was to benefit from both spatial and temporal resolutions of the available products. Both the budget and temporal view on the carbon cycle includes surface-atmosphere C fluxes from the terrestrial biosphere, fossil fuels, fires, land use change, rivers, lakes, estuaries and from the open ocean (figure 17). Although the budget cannot be closed at the global scale, for the first time, global maps of the most important carbon fluxes, which are all directly derived from observations were provided. The resulting spatiotemporal patterns of C stocks and fluxes and their uncertainties inform about the needs for intensifying global carbon observation activities. In particular the land sink is currently overestimated from data (probably because of underestimation of respiration) and needs further investigation. Moreover, WP7 provides priors for inversion exercises or to identify regions of high (and low) uncertainty of integrated carbon fluxes. Data synthesis can also be used as a empirical reference for other local and global C budgeting exercises.
Thirdly, a suite of methodological advances to inspect carbon cycle observations including trends, trend-changes, and hotspots in terms of extremes in carbon cycle observations amongst other methodological innovations. We developed methodological approaches to describe hotspots of variability across global gridded Earth observations and provided an overview (Del. 7.2). Specifically trends in the terrestrial photosynthetic carbon uptake over the last three decades (1982-2011) were quantified, points in space and time where trends have significantly changed were identified. Hotspots of high interannual variability in photosynthetic carbon uptake were also identified. These analyses were mainly based on four different data sets of gross primary productivity (GPP), ranging from data-driven estimates (using remote sensing data from satellites and point-scale measurements of carbon exchange between the biosphere and the atmosphere from eddy-covariance towers) to model output from dynamic vegetation models. The trend

analysis reveals several regions with strong trends in GPP between 1982 and 2011. Regions with strongly decreasing trends include the Sahel region, Central North America, Central South America and Mongolia (with a maximum of up to -6 g C m-2 m year-1). Regions with strongly increasing trends include Southern Africa, The Horn of Africa and Northern Australia (with a maximum of up to +6 g C m-2 year-1). Despite the shortness of the time series, we detect areas with significant break points in Central Sahel region (around year 2000), Southern Cen- tral North America (early 1990s), and Central South America (later 2000s). However, a key aspect is identifying hot-spots of variability, i.e. here extreme decreases in photosynthetic carbon uptake are mostly in arid and semi-arid areas. These include Northeastern Brazil, Central South America, Southeastern Australia, South Africa, Kenya, Tanzania and South Central United States. The detected extremes lead to a maximum decrease in GPP of up to 200 g m-2 year-1. Relating extreme events with variability we find that a few large-scale extreme events in GPP drive most of its global interannual variability.

Harmonization of input and output data streams (WP8)
The objectives of this work package were to choose and harmonize all input data streams for the different Carbon Cycle Data Assimilation Systems (CCDAS) based on the work done in WP-2-4-5 and other projects (CARBONES, MyOCEAN, COCOS) and to prepare a standardized protocol for the CCDAS outputs in order to facilitate the comparison of the results. The achievements include:
• Meteorological forcing: Two forcing have been used: ECMWF interim reanalysis (ERA-I) and “CRU-NCEP” dataset that combines CRU monthly forcing and NCEP meteorological forcing (see: “dods.extra.cea.fr/data/p529viov/readme.htm”)
• Atmospheric CO2 data: The standardized package produced at NOAA-ESRL, ObsPack that enables complete tracking and citation of all datasets from all contributing laboratories has been used.
• Land input data stream: We built a common fossil fuel emission product (see WP5) that was used by each CCDAS group. These emissions were prepared at 1°x1° spatial and 3-hourly temporal resolutions over the longest possible period (1989 to 2011), based on a recent product derived within the CARBONES project. A common set of Eddy covariance flux measurements for Net Carbon Exchange, Latent Heat and Sensible Heat fluxes (from FluxNet database) was prepared, including a correction for the energy balance when needed and the local meteorological forcing. Several satellite vegetation indexes have been used and we thus only reformatted them: MODIS-NDVI, SeaWifs-fAPAR, AVHRR-NDVI.
• Ocean input data stream: We used ocean data streams gathered at several archiving centers (PANGAEA/WDC-MARE, CDIAC) and wrote a synthetic description of the different inputs and validation datasets (deliverable D8.2) with their strength and weaknesses. These include: the surface ocean CO2 atlas (SOCAT database); the three-dimensional carbon, nutrients and physical oceanographic deep section data from discrete measurements (CARINA, GLODAP, PACIFICA databases); sea surface temperature and sea ice concentrations from remote sensing (NOAA OISST, OSTIA).
• Protocol for the CCDAS outputs: A common output protocol for atmospheric, land and ocean variables, following the standard “Climate and Forecast” convention with the netcdf file format was prepared. The cdl description files (separate for land, ocean and atmosphere variables) and the protocol were provided to all partners.
The input files and protocol can be access through a doods server (http://www-lscedods.cea.fr/invsat/PEYLIN/GEOCARBON/) and could be re-used by any following inter-comparison project. Most of the input files were also archived under the database established by MPI (http://www.bgc-jena.mpg.de/geodb/projects/Home.php).

Carbon cycle reanalysis products from several CCDAS efforts (WP9)
WP9 worked to consolidate several Carbon Cycle Data Assimilation Systems (CCDASs) with the aim to quantify continental to regional carbon balances. For the land, five systems (BETHY-CCDAS, JSBACH-CCDAS, LSCE-CCDAS, DALEC-CCDAS and CTRACKER_EU-CCDAS) assimilating different data streams allow to optimize either the parameters or the fluxes of state of the art land ecosystem models. For the ocean, two systems (MICOM- CCDAS and CMCC-CCDAS) optimize the parameters of an ocean model and one system used a statistical optimization scheme. Info on methodologies used by the different CCDAs can be found in the second reporting period.
Optimized net and gross land ecosystem carbon fluxes, above ground biomass, and net air-sea fluxes were provided on a monthly temporal resolution at 1°x1° spatial resolution. These results are compared under a dedicated web site (http://transcom.globalcarbonatlas.org/) with global maps and time series for regional totals and further evaluated and analyzed in WP13 (D12.1 and D13.1). Significant differences in the net land and ocean carbon fluxes are obtained, even between the systems that use the same constraint (i.e. atmospheric CO2).
Figure 18 illustrates the global annual land carbon fluxes obtained from 5 CCDASs. The global land carbon flux is around -1.5 PgC/yr over the 2000s, but with significant differences between the different systems. The DALEC-CCDAS has the smallest land sink (around -0.5 PgC/yr), while BETHY-CCDAS has the largest sink (around -2 PgC/yr). However the year-to-year variations are more similar across the systems as well as the long-term trend that show an increasing sink over the 2000s.
Figure 19 illustrates the ocean carbon fluxes for the different CCDASs. The global ocean carbon flux is around -2.2 PgC/yr over the 2000s, but with large differences between the different systems. The UIB-HAMOCC system has the largest ocean sink (around -2.8 PgC/yr), while CMCC system has the smallest sink (around -1.8 PgC/yr). The year-to-year variations are smaller than for land but not in phase across the systems. Significant differences in terms of long-term trend appear with increasing sink in LSCE-system after 2000 but decreasing sink in CMCC.

Regional CCDAS products for the Tropics (WP10)
WP10 developed two regional CCDAS systems focused on estimating tropical carbon fluxes. The two CCDAS are the CarbonTracker system and the LSCE pyvar system. The tropical fluxes differ from those at mid-latitudes because biomass burning is a much larger component of the carbon balance in this region, and because the vegetation is accustomed to year-round high radiation and warm temperatures for photosynthesis. We have obtained new estimates for the Amazon carbon balance for 2010 and 2011 with our 2 data assimilation systems. We have made use of the unique set of observations from the Amazon aircraft profile sampling by Gatti et al. (2014). Within the CarbonTracker system, we have focused on different biomass burning estimates. We included estimates from SiBCASA-GFED4, GFAS and FINN. The GFED4 emissions were optimized using IASI CO observations. All results from the inversions with the 2 systems lead to a higher carbon uptake in the wetter year 2011 compared to drought year 2010. The magnitude between the systems varies substantially: the CarbonTracker systems result in a net sink in 2011 and a source in 2010, whereas the LSCE system (with Gatti) find a net sink in both years. The difference between both years (figure 20) is in line with the earlier findings of Gatti et al. (2014), although we find a somewhat smaller difference. Table 1 summarizes our estimates of the Amazon carbon cycle and shows WP10 estimates of the total carbon fluxes as well as a separation between the biomass burning and net biome exchange fluxes for both years. Constraining biomass burning emission estimates

is critical to improve our estimates of the Amazon carbon balance. Future efforts are focusing on optimization using the FLUXNET data as well as parameter optimization of the LSCE ORCHIDEE biosphere model. Furthermore we will look into the following years 2012-2014.

CCDAS products at the national scale (WP11)

The importance of assessing the suitability of regional scale inversions is obvious: such inversions present an improvement over the global ones, only if they yield higher accuracy at higher spatial scales, or present flux estimates that can be observed at the relevant scale. This implies a discussion of the error sources (including structural uncertainty of models), and of the problems that are involved in validating the inversion results

Regional scale inversions were set up with two different systems (JENA, VU-VUmc) to provide insight on the constraint of atmospheric observations on biosphere-atmosphere exchange of CO2 at regional scales. The error structure has been shown to significantly impact the posterior flux estimates. Results suggest that in case of a synthetic experiment with a significant bias between “true” and a-priori fluxes, large correlation scales are favoured. However this cannot be justified from model-data residual analysis for fluxes at eddy covariance sites. Note that a significant bias in the a-priori fluxes cannot be excluded per se, as the two biosphere models used in the Jena system have both been used to generate a priori flux fields for inversions; the true fluxes could in the most benign case be in the middle of the two models, yielding a bias in prior fluxes that is half the difference between the two.

Short spatial scales restrict the spread of information and therefore limit the ability of the system to correct fluxes at longer distances. This is obvious in the Jena inversion system and in the VU-VUmc system targeting pixel-based scaling of gross fluxes. In addition when using short correlations scales, the a priori uncertainty, integrated over time and space, will not be large enough, which requires either simple inflation of the error covariance (as done in the VU-VUmc pixel inversion), or inclusion of additional degrees of freedom such as a long-term bias component (as done in the Jena system). The larger error correlation implicitly incorporated in the VU-VUmc parameter inversion leads to a spread of information away from the measurement sites. However, it is questionable whether this large-scale correlation is realistic, similar to the case of large spatial correlation scales in the Jena system.

When aggregating to larger scales, there is considerable reduction of uncertainty. With the Jena system (without inclusion of a long-term bias component), uncertainty reduction in annual EU wide flux ranging from 30% to 85% was found for a single measurement site, depending on spatial correlation length scale of the prior uncertainty. For the VU-VUmc system, error reduction for “aggregates” was estimated by comparing calculated fluxes with fluxes observed by aircraft. Means over the year of flight-data were used (winter data are not counted, as the winter fluxes are difficult to monitor), and prior and posterior fluxes were calculated for the flights. For some regions, the posterior differences with observations are half the prior differences, whereas there is little improvement for some other regions). Error reductions are similar for both methods.

Using the STILT-TM3 Jena inversion system (developed partially with ICOS-Inwire funding; see also D11.1) and the VU-VUmc inversion system applied to a network of 25 stations across Europe, we found (see figure 21) that the year- and season flux averaged for those countries in Europe which are well-covered by concentration measurements, were substantially improved (error reduction up to one half for the annual average, for substantially different inversion methods), which is a promising result. A problem is that such results depend on assumptions about the prior error structure (correlation length and time, eventual inclusion of bias as an unknown element) which is necessary to set up an inversion The rising number of degrees of freedom, compared to the area, leads to considerable indeterminacy problems. Nevertheless, both synthetic experiments and comparison of results with observations show that country-aggregated average flux estimates can be improved by regional inversions, compared to global inversions. However, high-resolution mapping of fluxes remains problematic, even with a dense observation network. In summary, the following choices have a strong impact on uncertainty reduction: the choice of the unknowns to be solved for, whether these are fluxes, scaling factors, or parameters, the choice of the spatiotemporal resolution of these unknowns, and the choice of the spatial correlation of the prior flux uncertainty.

Independent assessment of CCDAS products (WP12)

WP12 made an independent assessment of our CCDAS products for both land and ocean fluxes. In general, the GEOCARBON CCDAS systems reproduce observed features in the global carbon cycle well. Figure 22 summarizes the global budgets for our 5 data assimilation systems showing that quite a number of differences between our systems were found. The land sink varies between -1.9 and -3.2 PgC/yr, and the ocean sink is between -1.1 and -2.1 PgC/yr. The ocean sink compares well to the Global Carbon Project estimate of -2.5 PgC/yr (Le Quéré et al. 2014), when we take into account a correction of 0.45 PgC/yr for lateral carbon export by rivers. For the land we have looked further into a comparison of GPP and biomass stocks.

Figure 23 shows the comparison of the global seasonal cycle of GPP for our 5 systems as well as in comparison to the independent estimate of Jung et al. (2009) based on upscaled eddy-covariance data. The GPP estimates of DALEC and CarbonTracker match well with the independent estimate of Jung et al. 2009.

Subsequently, estimates of the standing biomass were compared to independent estimates of the FAO, Thurner et al. and Saatchi et al. The results are shown in figure 24 where CCDAS models tend to be high in their biomass estimates for the NH, similar to most TRENDY models. In the tropics, this overestimate is smaller when compared to Saatchi et al.

We also compared our results to independent atmospheric CO2 observations. We have looked at the latitudinal gradient for both the CarbonTracker and the LSCE system, and for CarbonTracker we have compared the simulated concentrations to those of the HIPPO and CONTRAIL aircraft campaigns. Figure 25 shows that CarbonTracker gets a good match to the observations at the surface, but at higher altitudes the model overestimates the CO2 concentrations by about 0.5 ppm. This can probably be explained by insufficient transport between the depleted air at the surface (due to photosynthesis) to the upper troposphere.

Synthesis and Integration of CCDAS products (WP13)

The results of several Carbon Cycle Data Assimilation Systems (CCDASs) have been synthesized and compared to other independent approaches (i.e. an ensemble of atmospheric inversions, Dynamic land/ocean Model simulations (DGVMs), and CMIP5 model simulations). Figure 26 compares the mean net carbon balance of the different CCDAS listed in WP9: 4 global systems, 1 land-only system and 2 ocean only systems. Figures 27 and 28 compare the interannual flux variations of the different approaches for land and ocean.

Land fluxes:

The CCDAS results corroborate a global net land sink of 1.3±0.5 PgC/yr for the 2001-2009 period (natural exchanges plus biomass burning). Note that the optimized natural land flux depends on the biomass

burning flux that is imposed in each system. The spatial distribution of the carbon sink is in favour of i) a large sink in the North (from 0.8 to more than 2. PgC/yr) except for one system that has a positive flux (DALEC), ii) nearly neutral tropical CO2 exchanges (except for DALEC) and iii) a small sink or source in the South (except for BETHY). At the regional scale, the model differences become too large to draw robust conclusions. Additionally, we observe a significant trend of around 0.2 PgC/yr increase during the last decade (2000s) and such trend is more pronounced for the northern land ecosystems (> 30°N).
For the Northern land, the TRENDY models show a large spread and poor coherence in the inter-annual flux variations (IAV), except for a few periods where most models agree (i.e. 2004, 2006). On the other hand, the atmospheric inversions show more coherence in the estimated northern land flux IAV, with for instance a positive flux anomaly in 1994 and 2003 not observed in the TRENDY models. The inversions show also a coherent and significant increase of the land carbon uptake during the last decade (2000s), compared to the 90s (see Peylin et al., 2013). The 5 CCDAS approaches do not provide similar coherence than but if we exclude JSBACH that has only 3 years we obtain also a trend during the 2000s with increasing land carbon sink. Note that differences between LSCE and BETHY for the northern land flux anomalies are primarily due to differences in the respiration fluxes while the photosynthesis flux IAVs tend to have a much stronger agreement than the net CO2 flux (not shown).
Overall, the CCDAS results fall in between the flux estimates from standard DGVMs and from atmospheric inversions. The assimilation of atmospheric CO2 concentrations into these process-based models (through model parameters optimization) provides a strong and unique constraint on the seasonal cycle of the CO2 fluxes (not shown), reconciling the initial discrepancies seen in the DGVMs as well as on the inter-annual flux variations (IAV). CCDASs further offer the possibilities to diagnose the optimal contribution from Gross Primary Production (GPP) and Respiration.
Ocean fluxes:
Different model approaches corroborate an ocean sink strength of 2±0.6 PgC/yr around year 2000 with a trend of 0.2 PgC/yr increase during the decade centred on this year. Hot spots for air-sea CO2 flux variability are the polar regions and the equatorial Pacific. The year to year flux variations appear to be much more coherent in the atmospheric inversions (following the major El-nino, la nina oscillations) than the in the ocean models, while the few CCDAS do not provide a coherent picture yet. Ocean carbon data assimilation procedures for CO2 sink fluctuations are still in their infancy. At present, the results constrained by assimilation do not differ significantly from synoptically forced forward models. Therefore, the latter can well be used for ocean sink determinations at present until ocean carbon data assimilation procedures have been further developed including a time consuming and costly optimisation of the mean ocean state. Air-sea CO2 flux variability is caused by a complex interplay between climate variability and variability of ecosystem processes linked to physical boundary conditions. A rigorous and unambiguous process attribution on regional as well as global air-ocean CO2 fluxes is not possible at present and subject of specifically targeted studies. However, it is virtually certain, that changes in physical climate boundary conditions for the biogeochemical models are essential for appropriate quantifications of air-sea CO2 flux variability.
Overall, such analysis represents the first comparison of its kind; it highlights the potential of CCDASs and pave the road of future directions to investigate.

Global Carbon Observing system accuracy requirements and network design (WP14)
The objective of WP14 was from to start from the overarching science questions and needs formulated in the GEO Carbon Observation Strategy Report and to build on this to:

- Describe the current components of a Global Carbon Observing System and the notional requirements for a future carbon observing system that would be relevant for delivering a sufficient knowledge of the C-cycle and monitoring the effectiveness of mitigation policy
- Assess (notional) requirements of accuracy for the C fluxes and stocks that must be observed at different scales to provide a sufficient knowledge of the carbon cycle
- Estimate the uncertainty reduction from a realistic expansion of existing networks, including satellite observations of GHG column mixing-ratios, and the information content of space borne and in-situ biomass measurements for constraining land use fluxes and carbon uptake by intact forests.
- Estimate the feasibility, scale, and potential capabilities of fossil fuel emissions observing system using radiocarbon atmospheric stations, and emerging satellite data.
- Estimate the potential of 13C in CO2 and O2/N2 to discriminate and quantify abiotic and biological source/sink carbon processes.
- Provide nominal cost estimates and a synthesis of the uncertainty reduction.

These objectives have been met and several publications have been produced (or are in preparation). A joint publication using costs for a biomass observing system to estimate the economic benefits of REDD+ is also in preparation in collaboration with CMP7.

For three major of global C observation data-streams, performance assessments (OSSE – Observing System Simulation Experiment) were conducted with models that transform the observed variable and its assigned uncertainty structure into the geophysical quantity of interest. For instance, atmospheric inversions were used to derive flux uncertainty reduction, a statistical model was used to derive the robustness of continental scale GPP estimated by eddy covariance flux towers up-scaling. In OSSEs, a different density, coverage, revisit and accuracy of different observing capabilities can been be tested for the ability to meet overarching requirements on the geophysical variable of interest, for instance CO2 and CH4 fluxes or biomass carbon. The three global C observation data-streams that have been analyzed are 1) eddy covariance flux tower networks (for their ability to estimate GPP and Evapotranspiration at large - continental - spatial scales), 2) in situ and space-borne observations of CO2 and CH4 concentration gradients for their performances to determine regional flux budgets at seasonal and annual scale, and 3) biomass measurement from space.

In addition, the use of carbon cycle tracers has been investigated quantitatively, for 1) 14C in CO2 to verify national scale declarations of fossil fuel CO2 emissions, 2) 13C in atmospheric CO2 to discriminate between vegetation-atmosphere fluxes and changes in the water use efficiency of ecosystems e.g. during drought and 3) O2:N2 atmospheric observations to constrain air-sea fluxes of CO2.

The different results have had socio-economic impact and wider societal implications by feeding into the regular update of the GEO workplan, by helping the cost effective design of space Missions (such as CarbonSat selected in phase-A by ESA) and of in situ networks, and by accelerating awareness for using systematic carbon observations in support to climate policy.

Carbon Observation System for Tropical South America and steps towards Tropical Africa (WP15)

WP15 achieved the following objectives:
- extension of the forest plot monitoring in Africa and Amazonia, and detection of declining biomass carbon sink in Amazonia. The GEOCARBON Amazon forest inventory network (Task 15.1) showed that the forest biomass carbon sink is showing a long-term decline (Brienen et al 2015, Nature), and how ground-based inventories diverge from satellite-based estimates of forest biomass (Mitchard et al 2013). Figure 29 shows the Amazon-wide network analysed in Brienen et al (2015, Nature) while figure 30 shows a key

result from Brienen et al (2015), revealing how increased in productivity have been flattening out, but rates of mortality are increasing, resulting overall in a declining Amazon biomass carbon sink over time. This is the first direct evidence of possible saturation of the tropical forest carbon sink.
- development of intensive monitoring time series in South America and Africa, leading to detailed quantification of effects of drought on Amazonian forests. The intensive monitoring sites in Amazonia showed how the Amazon forest carbon sink responded to the 2010 drought, a result consistent with the airborne greenhouse gas observations (Gatti et al 2014 Nature, Doughty et al. 2015 Nature). A similar network is now established in Ghana and Gabon and first analyses are being completed. For each site a full carbon cycle description was developed, quantifying the major components of net primary productivity and heterotrophic and autotrophic respiration. An example is given in the figure 31 (for the plot Tambopata 05).
- response to the 2010 Amazon drought . Figure 32 shows how the carbon cycle plots give insights into the sensitivity of forest carbon cycle to drought (from Doughty et al, 2015, Nature). The studies how NPP was not diminished during and after the drought, but autotrophic respiration did decrease. Heterotrophic respiration also showed no response to drought. This work gives a powerful example of how intensive carbon monitoring can give unique and vital mechanistic insights the carbon cycle of ecosystems and contribute to a global carbon monitoring system. The results from this ground-based study are consistent with the GEOCARBON-supported airborne CO2 concentration data reported by Gatti et al (2014) in Nature.

Carbon balances and CCDAS applications to Tropical South America and Tropical Africa (WP16)
The aim of WP16 was to use the data provided by this project to calculate greenhouse balances primarily for tropical South America and to lesser extent also for tropical Africa. The data are as follows. Firstly, for South America, regular GHG measurements of the lower troposphere using small aircraft (figure 33). Secondly regular forest inventories at a widespread forest plot network (both Africa and South America). Thirdly comprehensive carbon pool measurements at a sub-selection of forest plots. Fourth targeted process studies of GHG fluxes at a limited number of locations and finally remote sensing observations of land use change and fire emissions. Synthesis of the data for purpose of estimating carbon and GHG gas balances is achieved through a hierarchy of data analysis, flux estimation approaches using atmospheric transport models in an inverse mode and data assimilation systems (CCDAS) which combine the various data types for estimation of greenhouse gas balances.
The flux estimation systems include back-trajectory based approaches which permit to estimate fluxes at the Basin scale and spatially more highly resolving systems employing atmospheric transport models and land vegetation models. More complex CCDAS systems include Carbon Tracker South America and a conceptually similar system based on the IPSL (Institute Pierre Simon Laplace) atmospheric transport and land surface model (called ORCHIDEE). These latter approaches combine information contained in lower troposphere greenhouse gas measurements and also modelled or remotely sensed state of the land vegetation to estimate greenhouse gas balances. The methane flux estimator uses the TOMCAT atmospheric chemistry and transport model developed at University of Leeds by M. Chipperfield.
The research undertaken as part of this work package has led to several, in part high-profile, publications some of them submitted and a few still in preparation (close to being submitted). The first study employing these data and drawing on GEOCARBON support has been published in Nature 2014 (Gatti et al.). Studies based on the various other approaches have either been submitted or are well advanced (Van der Velde et al., subm. to Global Biogeochemical Cycles, Wilson et al. subm. Global Biogeochemical Cycles,

Alden et al. to be submitted to Science, Barichivich et al. in prep). A technical paper describing the 4DVar estimation scheme based on the TOMCAT model has also been published. Finally we have published three summary papers of South American, African and tropical carbon budgets (Gloor et al. 2012, Valentini et al. 2014, Grace et al. 2014).
Using the data collected we have provided for the first time in situ data-based GHG balances for tropical South America. We could show a substantial sensitivity of the carbon Amazon carbon balance to climate with dry and hot conditions in 2010 leading to substantial carbon release partially via fires (Gatti et al. 2014, Nature, figures 33 and 34). On-ground observations at forests plots revealed that forest carbon uptake during the anomalously dry conditions led indeed to stalled productivity of the forests (Gatti et al. 2014, Doughty et al. 2015, Nature, in press).
Analysis of the atmospheric CH4 concentration data using back-trajectory based whole Basin balance calculations as well as simulations with atmospheric transport models using various CH4 emissions process models has permitted us to estimate for the first time the CH4 emissions from the Amazon Basin. See also figure 35.

Integrated CO2 budgets and their uncertainties (WP17)
The publication of annual updates of the global carbon budget supported by GEOCARBON brought together the carbon cycle research community to synthesise, on an annual basis, the state of understanding on the carbon cycle. GEOCARBON researchers have led the design and publication of three updates of 'living data' papers, which are pioneers in providing enhance transparency and traceability for important climate variables. The publications of the global carbon budget in the journal Earth System Science Data thus provides full methodology to support the evolution of the emissions of CO2 from human activities, and their partitioning among the atmosphere, land and oceans (figure 36). The key results emerging from this global annual update are:
1. All components of the carbon cycle have grown since 1959 except CO2 emissions from land-use change (Le Quéré et al., 2014). Particularly:
- fossil fuel emissions in the last ten years grew at 2.5% per year on average, higher than the growth rate in the 1990s (1%). Emissions in 2013 reached a record high of 36 billion tonnes CO2;
- emissions from deforestation remain low in comparison, at 3.3 billion tonnes CO2 in 2013, accounting for 8% of total emissions;
- fossil fuel emissions track the high end of emissions scenarios used by the IPCC to project climate change, due to smaller improvements in carbon intensity of GDP than expected in most scenarios, and continued GDP growth;
- atmospheric CO2 has continued to increase, and the land and ocean CO2 sinks to take up CO2.
2. The CO2 emissions quota to climate stabilization is limited, for any degree of warming (Friedlingstein et al., 2014):
- keeping warming likely (66% probability) below two degrees above pre-industrial requires the total amount of CO2 emitted since the pre-industrial period to remain below about 3200 billion tonnes CO2;
- society has used already about 2/3 of the CO2 emissions quota permitted to remain below two degrees. The remaining third of the quota is equivalent to about 30 years (one generation) at current emissions levels;
- total fossil fuel reserves (i.e. oil, gas and coal) exceed the CO2 emissions quota to two degrees. Thus, without use of carbon capture and storage, a part of today's fossil fuel reserves would need to stay in the ground if we want to achieve this target;

- the remaining CO_2 emissions quota will be shared amongst nations, by design or by default (Raupach et al., 2014). To meet a warming limit of 2°C with 50% chance of success, average global rates of emissions reduction over the next several decades typically need to be over 5% per year, accounting for the need to turn around presently growing emissions and not including possible negative emissions later in the 21st century.
An extension of the global carbon budget to regional land and ocean regions has been done during GEOCARBON, with detailed results published over Russia (Dolman et al., 2012) and Europe (Luyssaert et al., 2012) and over large land and ocean regions (Sitch et al., 2015).

Integrating CH_4 surface observations (WP18)
Natural wetlands constitute the largest individual source of methane to the atmosphere, and to date, the most uncertain one (Kirschke et al., 2013). WP18 was aimed at assessing the global emissions (mean, inter-annual variability and uncertainties) from natural wetlands for the past two decades using the land surface model ORCHIDEE, identifying sensitive parameters of the model regarding methane emissions, comparing the results of ORCHIDEE with other land surface models through a large model inter-comparison, and proposing a focus on the Amazon region, which is a key region for natural methane emissions.
Using ORCHIDEE model under different configuration allowed to span the range of uncertainty reported in the literature for global methane emissions 175-285 Tg/yr and synthetized in 2013 in Kirschke et al., a paper led by the component 6 of GEOCARBON. For comparison, the spread of the seasonal variations from nine land surface models forced by the same wetland surface shows the same range of uncertainty as the different configuration of ORCHIDEE (figure 37, lower left). In ORCHIDEE, the most sensitive parameters tested, with decreasing sensitivity, appeared to be the level of saturation used to trigger methane emissions, the filter linked to soil carbon content for peatlands, and the way the wetland extent is computed (prescribed or diagnosed). Overall these factors make the global methane flux vary with a factor of 2, as illustrated on figure 37 (upper left). Inter-annual variations of global wetland emissions reveals large year-to-year variations that can be linked with climate events and a small positive trend in the 2000s (figure 37, upper right) mainly linked with increasing tropical precipitations over the continents. The inter-annual variability appears much more robust among the different versions of ORCHIDEE as showed on figure 37 (upper right). This result, already noticed for CO_2 natural sinks has also been found for methane natural emissions from wetlands.
One main issue about reducing the uncertainties of modelled methane emission from natural wetlands is the ability to separate uncertainties due to the wetland extent from uncertainties due to the computation of flux densities. The question was addresssed by forcing 9 land surface models including ORCHIDEE with the same wetland map. The resulting interannual variability shows a good phase consistency (figure 37, lower right), highlighting the importance of the dynamics of wetland hydrology for the phasing methane emissions, but a poor magnitude agreement, showing the influence of the parametrisation of the flux densities on the magnitude of methane emissions.
The ensemble-mean annual emissions for nine different land surface models are plotted in figure 38 (left panel). Highest emissions areas are found in Tropical South America (Amazon basin), temperate South America, Canada, Western and Eastern Siberia, North India, North China, Indonesia, and Northern Europe. Uncertainties, computed as the standard deviation of the seven models used, show the largest values over common emission hotspots, suggesting that, albeit a large uncertainty on wetland extent in the different models (Melton et al., 2013), the main regions emitting methane are rather consistent between

models. In the end, the differences in wetland extent translate into a spread in annual means (±40% at global scale) and seasonal variations, which will be discussed next.
Despite the large remaining uncertainties in the methane cycle, the Amazon watershed has been identified as a key player in the mismatch between top-down and bottom-up estimates (Pison et al., 2013). The LPX-Bern Dynamic Global Vegetation Model (LPX hereafter) was slightly modified to represent floodplain hydrology, vegetation and associated CH4 emissions. At the Amazon Basin scale, we showed large uncertainty in the magnitude of wetland CH4 emissions. Sensitivity analyses gave insights into the main drivers of floodplain CH4 emission and their associated uncertainties (Ringeval et al., 2014, figure 38, right panel). In particular, uncertainties in floodplain extent and vegetation distribution can modulate the simulated emissions by a factor of more than 2. The best estimates, using the LPX model lead to simulated Amazon-integrated emissions of 44.4±4.8 Tg yr. Within the WETCHIMP experiment, and at this regional scale, the magnitude and the location of the emission differ significantly between models leading to annual emissions between 10 and 90 TgCH4/yr.

Integrating CH4 atmospheric observations (WP19)
Within WP19, global sources and sinks of methane were estimated using LMDZ and TM5-4DVAR on the basis of in-situ and satellite measurements. The data assimilation systems were modified for application to satellite measurements from SCIAMACHY and GOSAT. Furthermore we investigated to use of thermal infrared measurements from IASI. For use of these measurements, bias correction algorithms have been developed. The first Tasks of the WP dealt with the collection of atmospheric CH4 measurements to be optimized in the inversions or for validations of the inversion-optimized models. A deliverable report has been made available from this task (D19), which including tables with links to measurement programs and datasets that have been used (e.g. aircraft campaigns, satellite data portals, on ground satellite validation, etc.). A similar effort has been made regarding the collection of surface fluxes from emission inventories (EDGAR, TNO-MACC, REAS, etc.)
The SCIAMACHY and GOSAT satellite measurements have been assessed against TCCON and the TM5 model optimized using NOAA data. In the SCIAMACHY retrievals a bias was detected which varied with atmospheric humidity. Corrections were implemented in TM5-4DVAR either to account for the average difference with TCCON on-ground FTS measurements, or to optimize this error further inside the inversion (see Houweling et al, 2014 for further details).
Inversions have been carried out using the LMDz and TM5-4DVAR inverse modelling systems, cosntrained surface and satellite data for the period 2003-2010. For comparison we also included previously published results by Bergamaschi et al (2013) (see figure 39). The three inversions show a consistent inter-annual variability of large-scale methane emissions.
Figure 40 shows multi-annual mean CH4 emissions integrated over large regions, on the basis of our inversions. Different colours indicate different models and different ways to account for biases in the SCIAMACHY satellite measurements. Overall the global distribution of the emissions shows a reasonable consistency across the methods.
We have further investigated the causes of the transition from stable to increasing methane concentrations that took place in the year 2007 (see figure 41). The models agree on the tropics as the origin of this growth rate change. However, the flux resolving power of the inversions is insufficient to attribute the increase to a specific tropical landmass or emission process.
The inverse modelling results to wetlands emission estimates generated in WP18 were compared using the global DGVM Orchidee. The process model-derived wetland emissions do not show a strong signal of

increasing tropical wetland emissions around 2007 (Pison et al, 2013), suggesting either that this model misses an important process or that the inversion allocates a signal to tropical wetlands, which in reality comes from another process.

Synthesis of the global CH4 cycle (WP20)
The objectives of this WP were to provide an overall synthesis of the results obtained in WP18 and WP19, to assess the performance of the global CH4 observing system, and to formulate recommendations and priorities for further development of it. We have extended our synthesis by gathering published results from two additional land surface models and seven additional inverse models. These results were complemented by four inventories for anthropogenic methane emissions, five inventories for methane emissions from fires, and an ensemble of chemistry transport models to represent the chemical loss of methane in the atmosphere. This activity led to the largest synthesis of the global methane cycle to date, which was published at the end of 2013 in Nature geoscience (Kirschke et al., 2013). The publication has been used to produce the table 6.8 of the last IPCC report (Ciais et al., 2013).
The main findings, comparing bottom up (BU) and top down (TD) approaches, are as follows:
- bottom up estimates of global methane emissions sum up to an average global total of 678 Tg/yr, which 20% larger than derived from inverse modelling [514-560 Tg/yr]. The lack of constraint on global bottom-up estimates, contrary to top-down inversions, suggest overestimation of the bottom-up global natural emissions;
- for the period 2000-2010 the average source-sink imbalance is estimated at 6 Tg/yr, which is substantially smaller than in earlier decades [34 Tg/yr and 17 Tg/yr, for respectively, the 1990s and 1908s];
- in the 2000s, natural wetland emissions (TD: 142-208 and BU: 177-284 TgCH4.yr-1) and agriculture/waste emissions (TD: 180-241 and BU: 187-224 TgCH4.yr-1) dominate CH4 emissions, followed by anthropogenic fossil fuel emissions.
- geological sources of methane, both natural and from the human exploration of fossil fuels, account for ~156 Tg/yr, which is consistent with an analysis of 14CH4 atmospheric measurements. However, fossil emissions of this magnitude are not confirmed by a recent analysis of the global atmospheric record of ethane, which is co-emitted with geological methane.
The regional distribution of the emissions is summarized in figure 42, highlighting large emissions from agriculture and waste treatment in China (TD: 29, BU: 28 TgCH4.yr-1) and India (TD: 27, BU: 22 TgCH4.yr-1). However, per capita CH4 emissions in India and China are still 35% and 85% of the mean for OECD countries. Emissions from natural wetlands dominate in tropical South America (TD: 28, BU: 58 TgCH4.yr-1) and Africa (TD: 36, BU: 24 TgCH4.yr-1) with significant emissions in Southeast Asia, temperate South America, boreal North America and boreal Eurasia. Tropical South America shows the largest regional discrepancy between TD (17-48 TgCH4.yr-1) and BU (39-92 TgCH4.yr-1) wetland emissions.
The TM5-4DVAR and LMDz inversion systems have been used to extend our analysis of global methane beyond 2010. The aim was to combine the global scale analysis of CMP6 with the Tropical focus of CMP4 in order to investigate the impact of Amazonian drought of 2010 on methane emissions from the Amazonian floodplains (figure 43). According to our inversions, the difference between the Amazonian CH4 emission in 2010 and 2011 remains within a few Tg, in good agreement with simulations using the process model Orchidee.
On the basis of our synthesis, the following recommendations are made for further improvement of the

global monitoring system of methane:
• A main priority should be the reduction of the uncertainty in natural wetland emissions. A large fraction of the uncertainty is due to uncertainties in the spatio-temporal dynamics of wetland area. This could be achieved by a better integration of water gauge data, hydrological models, and satellite remote sensing.
• Further development of operational programs to acquire flux measurements for different relevant environments and to integrate these data in a Fluxnet-type database, in order to improve process understanding, and to support the development land surface models.
• A better characterization of natural geological emissions, and to integrate the available information from process studies, including isotopic information, into gridded maps for use in inverse modelling.
• A systematic assessment of the uncertainty of anthropogenic emission inventories, separating the contribution of uncertainties in emission factors and activity data.
• The support of international inter-comparison initiatives to assess and improve the quality of chemistry transport models.
• To maintain the current surface monitoring capacity, and expand – where possible – in poorly monitored regions such as the tropical continents.
• Further development of techniques for measuring CH4 from space, to improve coverage and measurement quality. This will require extension of the validation network, and supporting in situ measurements for connecting remote sensing measurements to the WMO-GAW calibration scale.
• Extension of the global surface network with continuous measurements of methane isotopes, supported by field measurements to improve the characterisation of source signatures.

Costs-benefits (monetary and non monetary) analysis (WP21)
The different tasks performed under WP21 led to the following findings:
- concerning the impact of better carbon flux monitoring, large benefits (net of the investment cost) were found. This benefit refers solely to the impact through more stable carbon prices on investment into decarbonisation in the electricity sector (figure 44), so when accounting for additional benefits, the overall benefit could be much higher than the 170 million EUR net benefits found from avoided emissions under the 450 ppm target for a discount rate of 6%;
- as for the cost savings in achieving emissions targets under improved information on carbon fluxes, the benefit was measured by the (costly) errors that can be avoided by shrinking the possible range of fluxes under a REDD+ policy (figure 45). For example, a country which over reports their emission reductions from avoided deforestation will not be detected when the range is relatively wide, but the emissions target is not reached and may eventually have to be offset in a more costly manner. On the other hand, if policymakers want to be reasonably certain that the emissions target is met; they will have to abate up to the outer end of the range, thus likely paying too much. Reducing uncertainty by having better information about the actual fluxes will reduce the error potential on both sides, which is exactly what is valued in this study. The benefit sums up to approximately 30 billion EUR, where we cover the major – pan-tropical - emitters of deforestation emissions;
- finally, the full model linkage between IIASA's land use model (GLOBIOM) and CMCC's WITCH model established enables an analysis of the deforestation emission results and its impact on mitigation portfolios within WITCH.
Clearly, the assessments of benefits from improved observations prepared for the GEOCARBON project and presented in this report can only be assumed to be snapshots of the true, overall benefit. In reality, many more benefits result from climate change mitigation and conservation of forests than the decrease in

policy cost that has been the focus of our studies. Improvements in air quality and thus health conditions are only one example. In addition, there is an invaluable benefit for scientific progress in understanding the carbon cycle and ultimately a better basis for decision-making in climate change policy. Other sectors will also be affected and so will actors that we have not taken into account in our modelling exercises. It is therefore clear that we only cover parts of the overall benefit. Yet, this benefit is already so large that it does justify the investment into a better carbon observation system (which is relatively small in comparison), which will hopefully serve as support for officials to justify the means invested into such equipment and the associated projects.
One of the main, longer-term outcomes of this effort is the Biomass Geo-Wiki (figure 46), which will ultimately lead to the provision of better information on global biomass, which is a necessary component to the development of national and international level REDD+ policies. Biomass inputs are also critical to Monitoring, Reporting, and Verification (MRV) frameworks of carbon inventories and will therefore provide a valuable resource for national governments in the future.
Potential Impact:
The GEOCARBON results are already affecting a wide range of people and processes, ranging from the research community, monitoring networks, decision makers, etc.
The unique C-cycle dataset compiled and analysed by the project is explicit in space and time over one decade and will provide many opportunities for further exploration. Importantly, the database (the GEOCARBON data portal: http://www.bgc-jena.mpg.de/geodb/geocarbon/Home.php) will be maintained in the long term, also through the link with the GEOSS Data Core system. End users can subscribe and download the desired data. The integrated view and the derived data basis will become a guideline for identifying gaps in future observation systems as well as serving as critical reference for coupled C-cycle/climate models. In addition, the comprehensive work on the different CCDAS systems is providing the research communities with improved tools to integrate, synthetize and visualize carbon results from a wide range of sources.
A prototype for comprehensive tropical GHG monitoring and understanding was developed. The proposed system allows to monitor large-scale changes (specifically rainforests) and what contribution the forests make to the global GHG trend. The impact to the scientific community, including also policy and economic implications, is significant: a monitoring system of this type is able to capture future changes going down to the question what the resilience of the forests is, particularly important in the key huge and unstable carbon reservoir of the tropical forests.
The three annual CO2 budgets published under GEOCARBON have received worldwide press coverage and have informed the climate policy process, particularly via the UNFCCC and IPCC frameworks. This important GEOCARBON contribution will survive well beyond the project end, with further developments of CO2 budget methodology, particularly as regional budgets become better constrained and more robust. Similarly, GEOCARBON initiated a global collaboration in the frame of the Global Carbon Project (GCP) also to estimate the CH4 budget, and this process will continue with expected global bi-annual updates. The measuring methodology and the following recommendations formulated for improving the global CH4 monitoring system will address the future research programmes on methane.
Integrating multi-scale and multi-gas observations and models to deliver new data and information products, will allow to: reduce uncertainties, provide independent tools for verification, and link the scientific aspects of the C-cycle with its socio-economic and policy implications.
GEOCARBON demonstrated also that the benefit from an improved C-observing systems, taking stock of the project results, is significant, in the order of hundreds of M€. Even though this assessment of benefits

was only partial, covering a couple of examples of the global observing system, yet it is already so large that it does justify the investment into a better C-observation system (which is relatively small in comparison).
It is expected that the impact and exploitation of all the above mentioned wealth of results will continue at least for the next decade. This will be ensured also by the continuation of the GEO Carbon Office (already secured for the next two years) and the full embedment of the GEOCARBON work in the frame of GEO, and the global C-community in particular. The GEOCARBON group is still a major component of the GEO Task CL-02 on carbon, and is actively contributing to the development of the new GEO Work Plan for the next decade (2016-2025) particularly for what concerns carbon and climate. Part of this work is the development of a GEO Flagship initiative on Carbon, with the key element to secure the continuation of the GEO Carbon Office in the long term, based on a more formalized structure and recognized role. If so, the GEOCARBON perspective will continue to guide the Global Carbon Observing and Analysis System in the long term.

Furthermore, the potential impact (including the socio-economic implications) and the main activities for dissemination and exploitation of results are described in more details here below, showing the connection with the relevant WPs.
The results of activities of WP1 were presented in several international conferences and workshop in Europe and USA (American Geophysical Union, San Francisco, December 2012; Global Vegetation Monitoring and Modelling conference, Avignon, March 2014; 5th EARSeL Land Use and Land Cover Workshop, Berlin, March 2014) and were published in both high-level peer reviewed scientific journals with a wide distribution (e.g. Nature, Bulletin of the American Meteorological Society, Biogeosciences) as well as in popular press for the wider communities (International Innovation).
The existing data products of upscaled GPP (WP2) are currently widely used as reference for calibrating terrestrial biosphere models and comparing simulated patterns of coupled Earth system models (the respective paper was cited 142 times since 2011). However, the coarse resolution and limitation to predict GPP only may limit its suitability for the next generation of models with higher resolutions. Likewise empirical analyses of land-processes such as the inspection of trends, anomalies, interannual variations, and extreme events are limited with the present products. Hence, having a novel high quality data product that exceeds the existing resolutions would allow for much more local investigations. A key improvement is including towers at previously unconsidered regions in order to better constrain the carbon fluxes of critical areas in the tropics where the major uncertainties are to be expected. The new FLUXNET dataset, although not yet fully released at the end of the project, will be an important step forward respect to the actual La Thuile FLUXNET Synthesis dataset. New sites, new consolidated processing, higher quality and uncertainty estimation will make this dataset a reference for future studies based on ground level measurements.
The work performed and the data produced in WP3 directly led or contributed to 18 peer review publications. It helped better understand and quantify the fate of carbon along its transit between the land and the open ocean. For the first time, the role of lateral carbon fluxes in the anthropogenic CO2 budget has been estimated (Regnier et al., Nature Geoscience, 2013; Bauer et al., 2013, Nature). Additionally, collaborations with international networks such as RECCAP and the Global Carbon Project have been initiated in order to better represent the land-ocean boundary and include some of the newly created estimates into the most recent global carbon budgets (LeQuéré et al., 2014). The data collected and produced by WP3 during the project have been compiled into interactive maps using the global

MARCATS/COSCAT segmentation which can be accessed online from the Geocarbon portal: http://www.geocarbon.net/index.php?option=com_content&view=category&layout=blog&id=31&Itemid=135. These maps provide 150 regional carbon budgets and are also a visual tool reach a wider public with information regarding the carbon cycle. In order to facilitate the use and exchange of these data with the rest of the carbon community, 0.5 and 1 degree resolution NECDF files were also created and uploaded on the GECARBON data portal.

Concerning WP4, the unprecedented observation-based quantification of the mean and temporal variability of the ocean carbon sink provides crucial constraints for the global carbon budget. Concretely, the net land carbon flux can now be computed by differencing against ocean carbon uptake estimates for each individual year, resulting in estimates that are much more reliable than what has been possible before. The Global Carbon Project's annual carbon budget has begun in their latest assessment to take these new constraints into consideration, but only as a check. It is being planned that through time, the currently largely model-based methodology will be replaced by the new observationally-based ocean uptake numbers. This knowledge is crucial for policymakers as it permits to track the CO2 that has been emitted in previous years through the Earth System, providing policymaker with an up-to-date information about how much of the emitted CO2 has remained in the atmosphere, and what has happened to the rest. Results from WP4 suggest that the ocean has continued to take up CO2 from the atmosphere at a substantial pace, and that his uptake may have accelerated in the recent years.

Overall, the comparison of several products made in WP5 provides qualitative information on fossil fuel uncertainties, given that they vary between regions and depend on the considered spatial resolution (with a large increase at fine scale, i.e. lower than 0.5°). Significant error correlations exists in space and time that should be further estimated, using for instance the FFDAS approach. A dedicated web site supports such analyses through an interactive visualization of the different products (maps and time series for an ensemble of regions): http://transcom.globalcarbonatlas.org The comparison of WP5 provides new information for carbon cycle modellers, beyond GEOCARBON.

The data basis provided by WP6 is of relevant to carbon cycle researchers beyond GEOCARBON. The long-term remote sensing data products have already and continue to be important elements of analytics of land-surface responses to climate forcing. The inversions of atmospheric CO2 are of uttermost importance to a wide range of on-going international efforts to better constrain the global carbon cycle – especially the question how to attribute inter-annual variations in the land fluxes.

The potential of WP7 is manifold: firstly, we anticipate that the data portal will be beneficial for the scientific community as well as the interested public (the infrastructural link to the GEOSS data portal has been established http://www.geoportal.org/ and can be ingested by them on demand) Between Jan 2013 and Jan 2015 more than 600 data downloads were registered, but most of these downloads have happened relatively recently and are mainly due to project external requests, indicating that we are currently becoming increasingly of use for the public. Secondly, the data synthesis activity is a complementary to existing global activities such as the global carbon projects annual budget. For the first time, we provide a space and time explicit view observation driven view on the global carbon cycle. The resulting spatiotemporal patterns of C stocks and fluxes and their uncertainties can inform us about the needs for intensifying global carbon observation activities. Thirdly, the suite of tools developed in GEOCARBON (ranging from gap-filling large spatiotemporal data sets, detection of trend changes, to identifying hotspots of variability) could become key elements in global analytics. For instance, we show that we can evaluate CMIP5 models from the perspective of impacts of climate extremes on the C cycle.

The WPs from 8 to 13 are part of CMP2 for the improvement of the Carbon Cycle Data Assimilation System (CCDAS) and also had important impacts at different level, from the scientific community to policy implications. For example, constraints identified for providing national scale inversions (showing that at national scale significant error reduction are possible, up to 50% of the annual values) have the potential to develop the method for future use in emission monitoring schemes under UNFCCC commitments. However the work carried out also clearly identified the shortcomings and problems that need to be solved, and this should address next research activities.

More in general, the comparison of CCDAS results to other approaches, carried out within GEOCARBON, is important because highlights the benefit of assimilating various data streams into current process-based land ecosystem models and the critical issues that remain to be resolved to improve future model data fusion schemes. A comprehensive analysis of the potential of model parameter optimization using various data streams, was conducted. Although not mature enough, these data assimilation scheme open the road for new insight on the carbon cycle and how to reduce future uncertainty in the prediction of the land carbon budgets and thus the future climate change. Finally it identifies directions for future research in order to improve data-model combined approaches for improving our knowledge about the global carbon cycle.

WP14 (CMP3) started from the overarching science questions and needs formulated in the GEO Carbon Strategy Report and to build on this to assess the needed components of a global carbon observing System and the notional requirements for a future observing system that has to be relevant for delivering a sufficient knowledge of the carbon cycle and monitoring the effectiveness of carbon mitigation policy. Cost estimates and uncertainty reduction were also estimated. For three major of global C observation data-streams, performance assessments (OSSE – Observing System Simulation Experiment) were conducted with models that transform the observed variable and its assigned uncertainty structure into the geophysical quantity of interest. The different results have had socio-economic impact and wider societal implications, for instance in a practical by helping the cost effective design of space Missions (such as CarbonSat selected in phase-A by ESA) and of in situ networks, and by accelerating awareness for using systematic carbon observations in support to climate policy. In fact these results should guide future climate policy in support of a sustained global carbon observation and analysis system. Several publications have been produced (or are in preparation).

The main legacy of WP15 and WP16 (CMP4) is a prototype for comprehensive tropical greenhouse gas monitoring in Amazonia (and potentially to Africa), monitoring the main components needed to determine and understand carbon balances, and more generally greenhouse. Besides providing a measurement infrastructure and concept which permits us to monitor large-scale changes of the system – specifically of the rainforests – and what contribution the forests greenhouse balances make to the global greenhouse trend, we also have developed suitable atmospheric transport and chemistry models coupled to land vegetation models. These tools are designed to provide comprehensive synthesis of the different data-streams. Particularly they permit spatial and temporal resolution of greenhouse gas fluxes. We are convinced that a monitoring system of the type we have developed is able to capture those future changes, which we really want to know, boiling down to the question what the resilience of the forests is. This system can be replicated in the other tropical areas that are a key component of the global carbon cycle. The efforts led to several high-impact publications (of which one in Nature) which have also been reported on in newspapers and television like the Guardian, der Spiegel or BBC.

WP17 (CMP5) helped to build strong societal impact for Europe in two ways:

1. GEOCARBON informed national and international climate policy within Europe and abroad. The annual

update of the 'Global Carbon Budget' was presented to policymakers in special sessions of the UN Conference of the Party in Doha (2012), Warsaw (2013), and Lima (2014). The press releases and extensive outreach efforts by the team have led to worldwide diffusion of the results every year, with increasing coverage reaching an estimated 2500 press articles in 2013. The various products released with the carbon budget (the ESSD paper, PPT presentation, database, carbon atlas) were accessed by at least 20,000 people in the week following the last release (see full detail in Deliverables 17.2). This effort constitutes one of the largest efforts to synthesise and make accessible some of the most important data to assist in climate policy discussions, in a transparent, well-documented, and easily accessible way.
2. GEOCARBON helped forge international collaborations within and outside Europe, and helped promote the international leadership of European scientists in global environmental change and sustainability research. It has cemented an international activity, the global carbon budget, which will last well beyond GEOCARBON. In particular, GEOCARBON provided the essential support to produce the first 'living data' version of the Le Quéré et al. (2013) paper, which was a substantial effort to clarify and document the full methodology of the carbon budgets. This living data paper, now in its third edition, has grown to an authorship of over 50 scientists, which are committed to keep their data analysis up to date for the benefit of all.
The methane role in the global carbon budget, addressed by WP18, WP19 and WP20 (CMP6), was the weak component of the system. Thanks to GEOCARBON significant progresses were made to strengthen it and the results are guiding future research in this field, with implications also beyond the research community. Reducing uncertainties on the global methane budget is important to design adequate greenhouse gas emission scenarios for the future. The present poor knowledge on methane emissions has a strong impact on our ability to project climate change for the next decades. One tipping point of the methane cycle is the very large (~100%) uncertainty on the emissions from natural wetlands. CMP6 progressed towards better representation of CH4 emissions at global level, particularly from natural wetlands. More work is needed to achieve reasonable uncertainties, but on-going comparisons started by GEOCARBON jointly with the Global Carbon Project methane (GCP-CH4) should allow maintaining the momentum for collaborative quantification of natural methane emissions. GCP-CH4 is an international initiative launched from GEOCARBON with the intention to publish bi-annually updated methane budgets and already visible and accessible for the general public, other scientists or policymakers (http://www.globalcarbonproject.org/methanebudget/13/hl-compact.htm). The GCP-CH4 effort will allow a continued assessment of the global monitoring system of methane in the coming years.
Presentations of the results have also been made at AGU fall meetings in 2013 and 2014. The outcome of the methane synthesis derived in part from WP20 has been made available primarily through its scientific publication. In addition, it made an important contribution to IPCC 5th assessment report.
In WP21 (CMP7) large benefits (in terms of net investment cost) of installing a better carbon observation system, measured in two different ways, were found. In the first analysis, the benefit refers solely to the impact through more stable carbon prices on investment into decarbonisation in the electricity sector, so when accounting for additional benefits, the overall benefit could be much higher than the 170 million EUR net benefits from avoided emissions under the 450ppm target for a discount rate of 6%. Furthermore, the benefit of improved information on carbon fluxes is measured by the (costly) errors that can be avoided by shrinking the possible range of fluxes under a REDD+ policy. For example, a country which over reports their emission reductions from avoided deforestation will not be detected when the range is relatively wide, but the emissions target is not reached and may eventually have to be offset in a more costly manner. On the other hand, if policymakers want to be reasonably certain that the emissions target is met; they will

have to abate up to the outer end of the range, thus likely paying too much. Reducing uncertainty by having better information about the actual fluxes will reduce the error potential on both sides, which is exactly what is valued. The benefit sums up to approximately 30 billion EUR, where the major – pan-tropical - emitters of deforestation emissions are covered. Finally, a hard link between the WITCH model and IIASA's land use cluster (GLOBIOM) was established. This link enables an analysis of the deforestation emission results and its impact on mitigation portfolios within WITCH.

The major findings are as follows: expected Benefit of Carbon Monitoring Systems for REDD+ in Pan-Tropical Regions (2025-2050) very large > ~ 1.8 Billion USD Annually (~5% of REDD costs); costs of Carbon Monitoring Systems by comparison low ~ 50+ Million USD Annually; new carbon monitoring system allows policy makers to send energy sector investors a more reliable signal; coupled models show emissions avoided by reducing deforestation accumulate quickly in the next 30 years; establishment of the Biomass.Geo-Wiki.org – which is an open, freely available platform for visualizing global biomass data (satellite and in-situ).

Clearly, the assessment of benefits from improved observations prepared for the GEOCARBON project can only be assumed to be snapshots of the true, overall benefit. In reality, many more benefits result from climate change mitigation and conservation of forests than the decrease in policy cost that has been the focus of our studies. Improvements in air quality and thus health conditions are only one example. In addition, there is an invaluable benefit for scientific progress in understanding the carbon cycle and ultimately a better basis for decision-making in climate change policy. Other sectors will also be affected and so will actors that we have not taken into account in our modelling exercises. It is therefore clear that only parts of the overall benefit was covered. Yet, this benefit is already so large that it does justify the investment into a better carbon observation system (which is relatively small in comparison), which will hopefully serve as support for officials to justify the means invested into such equipment and the associated projects.

The exploitation of all the above listed results was maximized by the dissemination and coordination activities carried out in WP22 and WP23 (CMP8).

A range of dissemination activities were carried out since the beginning of the project. Strong linkages have been developed with the key actor groups in the field of global observations, starting from GEO to the other general global observing programmes (like GCOS, GOOS) and the ones more specific on carbon, like the Global Carbon Project (GCP), as well as the climate related initiative, i.e. UNFCCC and IPCC.

The dissemination activities included the preparation of dissemination material (logo, brochure, documents, articles), the project web site and data portal, the organization of meetings, conferences and other events, and the participation in external relevant events, particularly all the GEO Plenary, GEO Work Plan Symposia and the GEO European Project Workshops (GEPW) in the period 2011-2014. In all the above events presentations were given or information on the project were given and associated dissemination material was provided by representative of the project.

A GEO Carbon Office was established specifically to deal with the outreach activities and link with GEO, in order to align the GEOCARBON activities with the GEO Work Plan and provide coordination to the global carbon community; the office has been working for the whole duration of the project, still continuing.

A number (70) of scientific articles in peer reviewed journals were published, and many others are in preparation.

In conclusion, GEOCARBON, and its work in the frame of the GEO Task CL-02 on Global Carbon Observations and Analysis, are already well recognized, particularly but not only in the frame of GEO,. We had numerous and strong feedbacks (contacts by email, interviews, invitations to participate in scientific

publications, position papers, international events, discussions in relevant contexts, etc.) that GEOCARBON has already had significant impacts at different level, from science to socio-economic level, including policy. Policy makers need now more than ever reliable information to timely develop and implement effective policies. A better understanding of the global and regional carbon cycle (considering CO2 and CH4, i.e. the two strongest greenhouse gases) and more reliable “carbon-related” data and information systems have significant societal- and policy-relevant implications, being needed (among others) to: provide database status information to guide establishment of feasible and effective emission reduction targets (to be included in international treaties); verify the efficacy of upcoming mitigation policies, necessary to meet the objectives of the above mentioned treaties (scientific results allow an independent verification of emission reductions); create a baseline of carbon pools and fluxes (against which those policies can be verified); improve the ability to predict future changes by designing more robust scenarios (including those due to the implementation of the GHG management strategies); develop timely and appropriate adaptation actions (according to the provisions based on the analysis of the observations). Integrating multi-scale and multi-gas observations and models in efficient assimilation frameworks, as done by GEOCARBON, will allow to reduce uncertainties, provide independent tools for verification, and participate with economists, sociologists, and policy makers in the definition of society-relevant indicators of GHG emissions and of mitigation policies.
The work carried out by GEOCARBON has been contributing to the above needs, but the GEOCARBON legacy is not something temporary; what we have developed (in terms of new data, information, products, requirements and performance for a network design, cost-benefit analysis, networking and liaising with the relevant community, etc.) will continue to be exploited in the next years. This exploitation is ensured because of the importance of these achievements per se, and also because it has been planned to continue most of the GEOCARBON activities in the frame of the GEO Work Plan. All the GEOCARBON consortium members are heavily engaged in the GEO Task CL-02 “Global Carbon Observations and Analysis” and the GEOCARBON Project Manager is also the lead of this task. The GEO Carbon Office has already secured funding for the next two years, and efforts are ongoing to advocate for funding in the long term. Therefore the GEOCARBON group is continuing (fully coordinated with the global community of carbon cycle observations and analysis) to address the carbon related activities in the fame of GEO and contribute to the development of the new GEO Work Plan for the next 10 years (2016-2025) particularly for what concerns carbon and climate. The main objective is to raise the case of a Carbon Flagship initiative in the frame of GEO that stress the importance and urgency of an internationally sustained, integrated, global carbon observations and analysis system under the GEO umbrella, that should build on the GEOCARBON experience and be coordinated by the GEO Carbon Office, that will have more formalized structure, recognized role and effective capabilities.
This will provide an opportunity for the dissemination and exploitation of the project results at least for the next decade. Therefore GEOCARBON is not at all a closed project and its results will continue to guide the Global Carbon Observing and Analysis System in the long term.
List of Websites:
www.geocarbon.net

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