6. Due to the immense computational costs, the oceanic components of Earth system models cannot be integrated into equilibrium repeatedly in order to achieve a best possible spin-off start status for future climate scenarios. New **transport matrix methods** (Khatiwala, 2007) provide a tool for **calibration of the pre-industrial state for the global 3-D ocean** (including the slow parts of the system), which will significantly improve also the ocean carbon change behaviour of models used in future scenarios.
7. The evidence for vulnerable carbon sources and sinks needs to be explained and extrapolated to future conditions with appropriate models and analysis methods. We will employ **Monte-Carlo simulations** and **detection methods** for changing ocean carbon feedbacks to produce probabilistic projections on the vulnerabilities of the carbon sink and means to detect these vulnerabilities as early as possible.
8. Scientists assessing the changes in the ocean carbon cycling and those assessing ocean acidification impacts need to work hand in hand. We will provide the observational and modelling framework for impact researchers. Such a framework cannot be provided by these communities independently. We will produce **three-dimensional time series of ocean pH and carbonate saturation which are vitally needed by ocean acidification researchers** to strategically plan their experiments and to find early detection methods on occurring environmental and ecosystem change.
9. Major international assessments such as the **5th IPCC assessment report** of Working Group I, the **RECCAP (REgional Carbon Cycle Assessment and Processes)** programme of the Global Carbon Project, and the assessments **SOCAT** as well as **DeCChange** by SOLAS-IMBER working groups need input from organised communities with highest quality observational data and modelling products on the changing ocean carbon source/sink distributions. We will provide this input as expected from Europe through a consortium which is already involved in these assessments. The results from these assessments will provide **vital information for policy makers on climate change mitigation**. We will in addition inform policy makers directly on the new knowledge about the changing oceanic carbon sink so that policy makers can optimally tailor their decisions to the best available knowledge on carbon flows within the Earth system.
10. CARBOCHANGE will also synergistically work with the emerging **European Research Infrastructure ICOS** (Integrated Carbon Observing System; see: http://www.icos-infrastructure.eu) in order to establish a functioning long-term observing capability in Europe to watch the evolution of carbon sources and sinks on land and in the ocean and their vulnerabilities. The key members of the ocean component to ICOS participate in CARBOCHANGE. This project also aims at bridging the gap between the previous FP6 *Integrated Project* CARBOOCEAN and the operational start of ICOS. The European ocean carbon data streams will feed into the global observing system **GEOSS under the Group on Earth Observations (GEO)**, and into the related European **GMES** (Global Monitoring for Environment and Security) programme.

B.1.1.2 S&T objectives

The scientific and technological objectives of the project fully relate to all elements addressed by the call. These elements are *highlighted* below, to make the link between the project's objectives and the call clear. We further cross reference the specific sub-goals already here to the project's **Work Packages** (WP1-WP10), which have these sub-goals as respective WP objectives.

Objective 1 – Process understanding:
We aim at a quantification of the *key physical, chemical and biogeochemical processes* controlling net air-sea exchange of CO_2 in key regions of European interest. We will further identify, quantify, and explain the *feedback mechanisms associated to atmospheric CO_2 and resulting climate change* related to these processes.
The **sub-goals** for a better understanding of biogeochemical process and feedbacks are (**WP1**):
1. To quantitatively assess the magnitude of biological feedbacks on the ocean uptake of CO_2 by changes in vertical fluxes of organic carbon, testing as well as validating new model parameterizations and producing model output that will be used in model-model intercomparison.
2. To assess the role of lateral fluxes of carbon into the open ocean for variations in air-sea carbon fluxes, integrating models and observations
Delivery: We will provide a process identification of biological carbon cycling, improved process parameterisations for interactive carbon cycle climate models, upscaling of observational evidence to the large scale using models in order to quantify the impact on the atmospheric CO_2 concentration.
The **sub-goals** for a better understanding of physical process and feedbacks are (**WP2**):

1. To quantitatively assess the feedback on the oceanic uptake of CO_2 by changes in physical processes in the North Atlantic Ocean, including the Arctic Ocean and Nordic Seas, and the Southern Ocean.
2. To assess the representation of small-scale processes involved in the feedbacks (e.g. eddies) in carbon-climate models and guide development of improved subgrid-scale parameterisations

Delivery: We will provide new quantifications on the impact of climate induced changes in ice cover and ocean overturning from model sensitivity studies as well as from field data. The critical question of relevant model resolution will be answered through systematic experiments with ocean general circulation models.

Objective 2 – Future scenarios and vulnerability analysis:
We will achieve an assessment of *the vulnerability of marine carbon sources and sinks* with respect to *future emission scenarios* and *associated climate change scenarios* using coupled Earth system models through pursuing the following **sub-goals** (**WP 3**):

1. To assess the vulnerability of oceanic carbon sources or sinks with respect to future emission scenarios and associated climate change projections, on different time-scales (from multi-decadal to multi-centennial) through the use of Earth system models of variable complexity (ESMs and EMICs).
2. To identify the processes responsible for the simulated future changes in carbon sources and sinks and develop methods to determine the probability density distributions of their future evolution.

Delivery: We will carry out coordinated runs with several Earth system models (ESMs and EMICs) and analyse the results for a spectrum of possible IPCC emission pathways as established for the 5th IPCC assessment report including mitigation/stabilisation scenarios. We will address the short term (100 years) and long term (500 years) impact of CO_2 emissions on the ocean carbon sink evolution. A study on the detectability of human-induced variability of the ocean carbon sink will be carried out.

Objective 3 – Observing systems of the changing ocean carbon sink for integration with models
We will set up a network of observations which constrains the *magnitude and distribution of carbon sources and sinks under present and past climate change conditions* linking surface observations with time-series of subsurface ocean properties as well as interior ocean transports in key locations. We will use the combined network to detect and explain changes in the natural carbon cycle and the inventory of anthropogenic carbon in the ocean for *integration of these observations and state-of-the art models*. The goal is further, to perform a critical evaluation of the measurement network design in order to develop a long-term, sustained and efficient carbon observing system under climate change that can be carried forward and sustained in *synergy with international research projects* and specifically the evolving *European Integrated Carbon Observing System ICOS* (a European Research Infrastructure). The field data will provide the information on progressing *ocean acidification* both at the surface and in the ocean interior which is essential for – and cannot be provided by - scientists investigating the impact of ocean acidification on marine ecosystems.
Specific **sub-goals** for the surface observing system are (**WP4**):

1. Set up and evaluate a **network of observations** to track trends in atmosphere-ocean carbon fluxes in critical regions, and changes in both the natural carbon cycle and the trends due to the penetration of anthropogenic carbon in the ocean.
2. In the **North and Tropical Atlantic**, support and build on the prototype CARBOOCEAN network: Improve its efficiency of operation by a more co-ordinated approach. Improvements that need to be made are: better co-ordination to avoid data gaps due to the uncertainties of the shipping industry, more traceability in calibration, more accurate atmospheric measurements to be useable in inversion models, and useful in-water oxygen measurements. A coordination unit will be initiated to provide this extra level of support.
3. In the **Southern Ocean** use repeated transects of research vessels to enable a decadal picture to be built up in the Atlantic and Indian sectors. These large-scale / long-term investigations will be complemented by smaller-scale studies based on drifters' measurements, characterising the variability under-sampled by ship observations.
4. In the **atmosphere** we will undertake high-precision atmospheric observations of CO_2 and oxygen / nitrogen to enable us to test the use of regional patterns of atmospheric potential oxygen as an independent method of observing air-sea carbon fluxes over the North Atlantic.

Delivery: We will provide highest quality field data on pCO_2, DIC, pH, temperature, salinity, and oxygen which allow Atlantic Ocean and Southern Ocean carbon trends to be followed. These data are the pre-requisite for a successful calibration of ocean carbon models.
Specific **sub-goals** for observing the deep ocean (including time series and choke points) are (**WP5**):

1. To coordinate and conduct time-series and deep section measurements of the vertical structure of ocean carbon. New and existing high-frequency observations (<seasonal) at time series stations and lower-frequency (multi-annual/decadal) hydrographic sections will be used to estimate the variability of (regional

budgets of) natural and anthropogenic CO_2 and resolve internal ocean processes affecting the variability of oceanic CO_2 parameters.

2. To evaluate the carbon storage and its vulnerability in the interior ocean with respect to anthropogenic changes, oceanic circulation and biogeochemical processes, linked to model outputs and skills.

Delivery: We will collect and publish highest quality carbon system data on the interior ocean. We will produce an analysis of trends in anthropogenic carbon storage and its vulnerability to climate change. Time series data for calibration of ocean carbon cycle models concerning the seasonal cycle and interannual variability will be provided.

Objective 4 – Integration of observations with models including systematic model calibration

We will establish model systems for projections towards climate stabilization and global synthesis by *calibrating ocean carbon models* and *Earth System Models of intermediate complexity* with respect to observations. We will quantify the magnitude and distribution of carbon sources and sinks in the ocean in the *past* (over the industrial period and the recent past) and *present* by *data-model integration*. We will further determine specific governing carbon system parameters, inventories, and fluxes relevant *for improved quantification of the ocean carbon cycle under ongoing and future climate change* and as input for studies on the impact of large scale *ocean acidification*.

Specific **sub-goals** of the activity on model calibration are (**WP6**):

1. To integrate the ocean carbon models with observations available from WP4 (surface), WP5 (interior, time series) and WP8 (synthesis) and calibrate the biogeochemical parameters for accurate reconstruction of carbon and related tracers on different time scales. Advanced stand-alone models and a coupled terrestrial-ocean model will be used over decadal time scales, EMICs over centennial time scales and stationary transport matrices for millennial time scales.
2. To provide the calibrated models for reconstructions (hindcasts), for climate simulations in WP3, for comparisons in WP7 and for the synthesised assessment in WP8.

Delivery: A series of ocean carbon cycle model systems which will have been systematically calibrated through parameter adjustment with respect to observations on the changing ocean carbon sink will be provided to the community for exploitation in future scenarios, vulnerability analyses and ocean carbon budget compilations.

Specific **sub-goals** of the activity on model-observation/model-model comparison are (**WP7**):

1. To compare data-based estimates concerning ocean carbon and related tracers to simulated results from ocean carbon cycle models, both in forced mode (50-year hindcasts) and in coupled mode (part of Earth System Models).
2. To develop regional data metrics and use them to evaluate and weigh these models to provide optimal estimates for the changing ocean carbon sink (preindustrial through modern to 2100 and beyond) and carbon-climate feedbacks

Delivery: We will achieve a systematic performance assessment of the carbon cycle models with respect to observations using novel skill score metrics. The models' feedback behaviour will be analysed with respect to the models' ability to reproduce the observations.

Objective 5 – Synthesis for scientific assessments, policy makers, and international synergies

We will synthesise the results from observing systems and modelling achieved under objectives 1-4 as input to *relevant policies* and for *enhancing synergies with international projects* on carbon budgets. This work will directly feed into *international assessments* on the progressing climate change and related *climate change mitigation*.

Sub-goals for this synthesis activity (**WP8**, in part also the data-/management **WPs 9** and **10**) are to:

1. Produce high level synthesized products on an annual basis that provide key information on the uptake of CO_2 by the ocean at the regional and global level and on the regional drivers of change.
2. Synthesize information on the state of the ocean carbon cycle.
3. Synthesize information on the vulnerability of the oceanic CO_2 sink.
4. Archive and distribute data and information through advanced data management.
5. Communicate internally in the consortium, with the scientific community, the general public, and policy makers

Delivery: Annual estimates of the global and regional oceanic CO_2 sink including the uncertainty, driving processes, merged and quality checked data sets of highest quality ocean carbon data for the global ocean, global ocean carbon atlas, summary on the vulnerability of the carbon sink to global change. Dissemination of data and information to the world wide community and specifically to policy makers.

B.1.1.3 Concept of the project

The concept of the project is illustrated in Figure 1.1.3. The project builds on previous research projects dealing with marine carbon cycling and in particular the FP6 *Integrated Project* CARBOOCEAN. The proposed project will provide a closure to existing knowledge gaps on the ocean carbon sources and sinks in relation to other international projects, such as the FP7 collaborative project EPOCA (European project on ocean acidification) and the FP7 coordination action COCOS (coordination action carbon observation system). The results will improve policy guidance, integrate carbon observing and prediction systems (such as ICOS), and contribute to a sustainable management of the Earth system.

In order to achieve this high level of integration among the different teams that will collaborate in CARBOCHANGE we structured the project into three interactive **core themes** (CTs) and three **overarching work packages** (WPs) which cut across over all three core themes.**We have placed special emphasis to bring together observing and modelling scientists in each work package and core theme whenever advisable in order to overcome the disparities between the two communities**. The core themes themselves are structured into a series of work packages (WPs).

The **core themes** and the related project objectives from previous section 1.2 are:

CT1 - Key processes and feedbacks, future scenarios, and vulnerabilities (Objectives 1 & 2) (**WPs 1-3**)
CT2 - Observing system of ocean carbon changes (Objective 3) (**WPs 4-5**)
CT3 - Data model integration (Objective 4) (**WPs 6-7**)

The **overarching work packages** (addressing Objective 5) are dedicated to: Global **synthesis** and **outreach to policy makers** (**WP8**), data management (**WP9**), and management of the project (**WP10**).

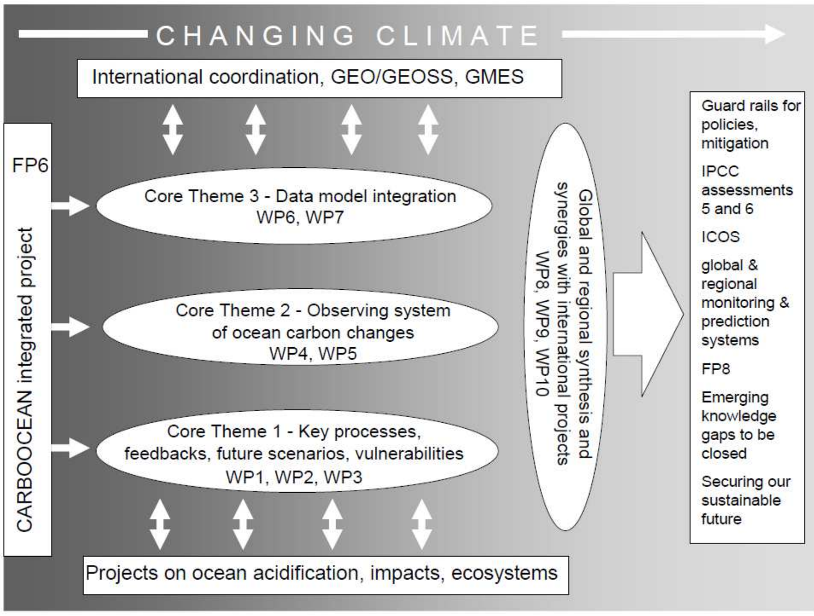

Figure 1.1.3: The concept of CARBOCHANGE.

CT1 - Key processes and feedbacks, future scenarios, and vulnerabilities (WPs 1-3), ***co-lead*** **Marion Gehlen (CEA/LSCE), Nicolas Gruber (ETH Zürich):**
It is the interplay between physical, chemical and biological processes that determine whether a particular ocean region behaves as a net source or sink with respect to atmospheric CO2. CT1 addresses the identification and quantification of key biological and physical processes, as well as their contribution to the feedback between the climate system and the carbon cycle. The CT will deliver an understanding of the observed and model-derived variability in the ocean carbon sink, attribute this variability to physical/chemical/biological processes and thus strengthen the forecasting skills of numerical models by the development of new process parameterizations. Coupled Earth system models will be used to upscale key feedback processes to the global scale, to determine specific vulnerabilities of the carbon sink, and to predict its influence on the future climate evolution. The coupled model runs will be of high importance to the 5^{th}

assessment report of the Intergovernmental Panel on Climate Change (IPCC). The spectrum of runs will also include stabilisation scenarios on feasible pathways for CO_2 emission reductions.

CT2 - Observing system of ocean carbon changes (WPs 4-5), ***co-lead*** **Andrew Watson (UEA), -Aida Rios (CSIC):**
In CT2, it is planned to combine and critically assess these observational approaches and their data in order to address key scientific questions, identify synergies between different observing platforms and strategies, and establish an efficient and coordinated design for the ocean component of the Integrated Carbon Observing System ICOS. The proposed observing network is global in orientation, being linked to the international community outside Europe. The European contribution will focus primarily on the Atlantic Ocean, including the Arctic Ocean as well as key sectors of the Southern Ocean. Cooperation with related programmes (e.g. projects focussed on European marginal seas) will be established wherever possible to extend the network.

CT3 - Data model integration (WPs 6-7), ***co-lead*** **Fortunat Joos (UBern), Nicolas Metzl (UPMC):**
CT 3 is dedicated to integrate observational data and models by developing and applying frameworks for systematic data assimilation and model-data fusion, by using the most comprehensive data sets, including those compiled in CT2, and by applying the most up-to-date hierarchy of models as well as the most important processes, including those used in and identified by CT1. The time and space scales of CT3 encompass seasonal to centennial and regional to global scales. Regional emphasis will be placed on the Arctic, the North Atlantic, and the Southern Ocean, regions of key importance for the global carbon cycle and where experience of the project team is extensive. Data-model integration will build on (i) assimilation methods, (ii) on model-data intercomparison relying on regional and global skill score metrics, on statistical detection-attribution methods, and on an innovative Transport Matrix Method for model evaluation.

Overarching WPs:
The results from the three core themes are merged in **WP8 on Global synthesis and outreach to policy makers** (co-lead C. Le Quéré, A.Olsen, D. Bakker) so that easily usable numbers and summaries are provided for concrete years. These results will merge directly into decisions on sustainable management as well as into international scientific assessments. **WP9 on Data Management** (co-lead B. Pfeil, R. Schlitzer) will ensure the direct embedding of the new data sets and model results in the international community and ensure long-term archiving, dissemination, and exploitation of results. **WP10 will manage the consortium** (lead: C. Heinze) including its interface with the European Commission.

B.1.2 Progress beyond the state-of-the-art

During the past 10 years, a series of EU funded projects has brought the European Research community on marine carbon cycle research to the very forefront in this field. These projects very specifically targeted to processes (ORFOIS – particle fluxes and carbon cycling end to end; IRONAGES – role of iron in the biological pump), climate modelling (GOSAC – model intercomparison, ENSEMBLES – decadal prediction with coupled models), and observations (CAVASSOO – surface CO_2 from voluntary observing ships, ANIMATE – oceanic time series measurements). The FP6 *Integrated Project* CARBOOCEAN (Marine carbon sources and sinks assessment) bundled the different disciplines and a new European marine carbon cycle network with excellent international network links could be established through this effort. CARBOOCEAN also included process studies on ocean acidification. The impact of ocean acidification is now studied in depth by FP7 project EPOCA, however, this project needs ocean carbon system observations and models from other projects as input to work with. A series of further ongoing FP6 and FP7 projects deal partly with ocean carbon cycling (EUROSITES and TENATSO – ocean time series, COMBINE – development of new Earth system model components and feedback analysis, SESAME and MEECE – ecosystems under climate change).

B.1.2.1 State of the art in research on marine carbon sources and sinks

B.1.2.1.1 Global ocean carbon uptake rates since industrialisation, in the recent past, and in future

The major pathways for carbon exchange between the different Earth system reservoirs are established (see Figure 7.3 in IPCC, 2007; Figure 10.1.1 in Sarmiento and Gruber, 2006). For the global ocean, time averaged ocean carbon uptake bulk numbers have been computed on the basis of observations and through use of models. Integrated over time since the beginning of the industrial revolution until 1994, the ocean has buffered about 42% of these CO_2 emissions (Sabine et al., 2004; IPCC, 2007, chapter 5). The fraction of the net CO_2 emissions taken up by the ocean was reduced to a mean of 37% during 1980 to 2005 (IPCC, 2007, chapter 5).

From decadal to century time scales, the ocean absorbs a fraction of the anthropogenic excess CO_2 in the atmosphere mainly through dissociation of CO_2 into bicarbonate under gradual consumption of the carbonate ions available. During this very well understood inorganic buffering process, the pH value of sea water inevitably sinks (ocean acidification) and with further increasing CO_2 levels, the ocean's buffering ability gets less efficient due to the non-linearity in the buffer system (e.g., Zeebe and Wolf-Gladrow, 2001). The future evolution of ocean carbon uptake depends strongly on the anticipated CO_2 emission scenario (e.g., Maier-Reimer and Hasselmann, 1987), where higher (faster) CO_2 emissions lead to a large build up of CO_2 in the atmosphere as the ocean cannot keep up with buffering the anthropogenic excess CO_2 and transporting it into the interior of the ocean. The coupled climate model future scenarios for the 4th IPCC assessment report (IPCC, 2007; ch. 10) were carried out with models that did not have an interactive carbon cycle. These model runs where unrealistically driven by prescribed CO_2 concentrations (and concentrations of other greenhouse gases) and not by CO_2 emissions into the atmosphere.

B.1.2.1.2 Major findings in the field of marine carbon cycle research during the recent past

Carbon cycle climate feedback using coupled Earth system models: In the past years a growing number of advanced predictive climate models have been developed, so called Earth system models, which include an interactive carbon cycling coupling and further biogeochemical processes. A comprehensive C^{4}MIP intercomparison of interactive carbon cycle climate models revealed that the carbon cycle climate feedback for both the land vegetation as well as the ocean is positive with time for an IPCC SRES A2 emission scenario (Friedlingstein et al., 2006). However, the model-to-model spread of 3 GtC/yr for the ocean carbon cycle feedback at year 2100 strength is large. While a series of models have confirmed a positive ocean carbon cycle feedback (e.g. Crueger et al., 2008), one study including an isopycnic ocean model revealed only a small feedback due to the compensating effects of changes in the buffer factor and the circulation pattern with climate change (Tjiputra et al., accepted for publication). Sign and amount of the ocean carbon cycle climate feedback depend also on the land carbon cycle components in Earth system models (Friedlingstein et al., 2006). For the coming 5th assessment report of the IPCC a growing number of coupled carbon cycle climate model simulations are required, which then will realistically be forced by greenhouse gas emissions. The scenarios include so-called "Representative Concentration Pathways" (RCPs) (for details, see: http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about) with mitigation scenarios aiming at an effective climate change and greenhouse gas limitation.

Considerable regional ocean carbon sink strength variations: One of the most important findings of the last years is the fact that the ocean carbon sink at regional to basin wide scale is far from being steady or monotonically acting, but undergoes considerable changes. During 2002-2005, the North Atlantic ocean carbon sink had decreased to only half its value for 1995-1996 (Watson et al., 2009; Schuster and Watson, 2007). The Southern Ocean is turning slowly from a source region of atmospheric CO_2 to a sink due to the rising CO_2 partial pressure of the atmosphere. However, a recent stalling or reversal of this trend was deduced both from observations and modelling at least for parts of the Southern Ocean (Metzl, 2009; Le Quéré et al, 2007). It is an alarming signal that the ocean sink decrease is particularly manifested in regions, which have been considered efficient storage areas for anthropogenic carbon. It is yet an open question whether these trends are transient due to natural variability or whether they represent more persistent alterations, e.g. due to a slowing down of the ocean circulation as anticipated for a climatic warming. The detection of the strong temporal variability oceanic sink/source distribution for CO_2 has fundamentally changed our view of the ocean as a reliable constantly working CO_2 sink. It is only from the recent more advanced observing systems for ocean carbon that this new view has been enabled. Attribution of the CO_2 flux variations to specific processes is as yet in its infancy due to the complexity of the interactions. Nevertheless, promising candidates for the changes are a weakening of the North Atlantic sub-polar gyre (Corbière et al., 2007) and an intensification of the Southern Ocean upwelling induced by stratospheric ozone depletion, associated wind stress changes and stronger upward mixing of older water masses carrying high CO_2 signatures (Lenton et al., 2009; Lovenduski et al., 2008).

Physical and biogeochemical feedback processes: Changes in the ocean circulation due to naturally and anthropogenically induced climate change can have a significant impact on changes in ocean carbon uptake, which are coupled to changes in ocean temperature and stratification (e.g. Plattner et al., 2001). Major climatic variability modes alter the CO_2 exchange between ocean and atmosphere, such as the North Atlantic Oscillation (NAO) and El Niño/Southern Oscillation (ENSO) (e.g., Thomas et al., 2008). The impact of a potentially ice free Arctic Ocean on the ocean's carbon budget is not as yet clarified, but may increase the oceanic uptake somewhat due to changes in biological cycling (ACIA, 2005, ch. 9), more efficient gas exchange due to a larger area available, and a series of other processes (Jutterström and Anderson, re-submitted after revisions). Changes in the biological carbon cycling due to climate change, rising CO_2/ocean acidification, and other human-induced drivers such as changes in nitrogen supply to the ocean (Duce et al., 2008) and changing dust deposition under climate change are still not well established, though many indications for potential mechanisms exists. Mesocosm and laboratory studies suggest a slight stimulation of organic carbon production, a decrease in bio-calcification, and a more efficient nutrient utilisation efficiency (stoichiometry change) under high CO_2 conditions (Zondervan et al., 2001; Riebesell et al., 2007). The overall impact on large scale carbon fluxes is not yet well established. While the direct effect of reduced $CaCO_3$ production on atmospheric CO_2 seems to be of minor importance (e.g., Heinze, 2004), secondary effects on particle fluxes may be more important (Klaas and Archer, 2002). The stoichiometry feedback may quantitatively more important, but neither sign nor extent are clarified under real world conditions. Changes in organic carbon particle fluxes due to rising temperature and pCO_2 could potentially have a significant impact on atmospheric CO_2 (Bendtsen et al., 2002; Wohlers et al., 2009).

Observing systems: A series of new developments in ocean carbon cycle observing systems has been made during the recent years. In particular surface ocean CO_2 partial pressure measurements from VOS lines (commercial lines serviced quasi-regularly by volunteering observing ships equipped with autonomous measurement systems) have proven as a cost efficient and rewarding tool. For the North Atlantic, this has resulted in the most precise basin-wide flux estimate available for any ocean part (or continent) with seasonal resolution (Watson et al., 2009). Unfortunately, as yet no sustained funding for these lines is available, though envisaged under the European Research Infrastructure ICOS (Integrated Carbon Observing System, see: http://www.icos-infrastructure.eu/index.php?p=hom). The North Atlantic VOS line observing system has been instrumental in identifying the large interannual CO_2 air-sea flux changes in the North Atlantic domain. Also the deep ocean sections collection with highest quality data has been substantially increased. High quality data syntheses for surface pCO_2 (SOCAT – surface ocean carbon atlas, see: http://ioc3.unesco.org/ioccp/SOCAT.html, most comprehensive surface ocean pCO_2 raw data base; Takahashi et al., 2009, pCO_2 climatology) and the deep ocean (GLODAP, Key et al., 2004; CARINA – Atlantic Ocean data set, see: http://www.carbon-synthesis.org/; e.g., Hoppema et al., 2009) have provided scientists with observational ocean carbon data of unprecedented quality, consistency, and coverage. Also, progress in the field of autonomous measurements has been made to equip floats and buoys with sensors and respective satellite telemetry to enable measurements in areas usually not covered by shipping routes or regular reoccupations through research vessels. Among these new developments, oxygen sensor systems are vital also for constraining the carbon system (as O_2 can be successfully used to discriminate between biologically- induced and physically-induced carbon fluxes in the Earth system). The deep section and surface ocean data have been combined with other oceanic biogeochemical tracers in order to reconstruct the increased load of dissolved inorganic carbon in the ocean due to uptake of human-produced CO_2. A series of different methods has been applied (such as ΔC^*, TrOCA, eMLR; e.g. Lo Monaco et al., 2005; Tanhua et al., 2007). One key result from these measurements are new estimates for northern and southern high latitude water column inventories of the anthropogenically induced carbon increase in the ocean. The unexpectedly high values coincide with the apparent – at least transient – sink strength reductions in large domains of the North Atlantic as well as the Atlantic sector of the Southern Ocean (Vázquez-Rodríguez et al., 2009).

Model developments and combinations of models with observational data: In Europe as well as world wide, climate research centres have developed new Earth system models or upgraded older systems. Existing and emerging hindcasts as well as future scenarios reveal the potential of these systems to provide internally consistent simulations of key features of the real climate system (e.g. Cox et al., 2000; Fung et al., 2005; Doney et al., 2006; Mikolajewicz et al., 2007; Tjiputra et al., accepted). These models are very demanding concerning supercomputing infrastructure for carrying out future scenarios. Therefore, also very coarse resolution Earth system models of intermediate complexity (EMICs) have been developed for scenarios exceeding ca. 500 years periods (e.g. Lenton et al., 2006; Müller et al., 2006; Brovkin et al., 2007). These models have a poor resolution, are thus not suited for simulations with regional significance, but are useful

for answering first order questions on long time scales (e.g. Plattner et al., 2008). New developments include a coupled physical-biogeochemical ocean general circulation model with isopycnic coordinates available (Assmann et al., accepted; Tjiputra et al., accepted).
In order to achieve optimal model predictions, the free model parameters need to be adjusted so that real world observations are reproduced in the best way without violating the model dynamics. Data assimilation methods originally developed for physical climate and Earth system component models are gradually also adopted for ocean carbon cycle models: the adjoint method (e.g. Tjiputra and Winguth, 2008) and the Ensemble Kàlman Filter (e.g. Gerber et al., 2009). Neural network techniques have been successfully employed for intelligently interpolating the VOS line surface ocean pCO_2 data in order arrive at basin-wide flux estimates (Telszewski et al., 2009). Inverse approaches under steady state assumptions have very successfully pursued for CO_2 fluxes (e.g. Mikaloff Fletcher et al., 2006; Gruber et al., 2009) and biogeochemical questions such as the fate of sinking particulate matter in the ocean (e.g. Usbeck et al., 2003).

B.1.2.2 Advance beyond the state of the art

CARBOCHANGE will close major emerging knowledge gaps which so far limit an accurate quantification of the ocean carbon sources and sinks. While for past decades only averaged changes in the ocean uptake strength for CO_2 could be deduced, and in general high variability could be identified for limited ocean basins, we proceed here to a more advanced level of quantification. We relate our description of the progress beyond the state-of-the-art to the same headings as in the previous section.

Carbon cycle climate feedback using coupled Earth system models: From the major climate research centres in Europe, we will employ their state-of-the-art Earth system models for the new IPCC emissions scenarios and RCPs (Radiation Concentration Pathway scenarios) which are of relevance for the IPCC 5th assessment report. The models are forced by CO_2 emissions, and the atmospheric CO_2 concentration is thus a prognostic variable in contrast to the bulk of coupled climate models as used in IPCC AR4 (WP3). This approach is advantageous for feedback quantifications and does not cause additional uncertainties in terms of ocean carbon sink analyses as the atmospheric CO_2 and climate evolution that forces the model ocean is know from the simulation itself. By using emission scenarios, we will explicitly exploit the strength of coupled Earth System Models to provide insights on ocean carbon sinks in the context of natural and anthropogenically forced variability of the entire Earth System, including interactions among atmosphere , ocean, sea ice and land. As an important step beyond previous scenario computations we will rigorously compare the Earth system models against observations and also intercompare the models (WP7). We will use new skill-score metrics with respect to observations in order to establish a valid and objective reality check for the models for the time period when reliable data are available. This is a decisive progress beyond the state-of-the-art and will render a more realistic view on the models’ ability to reproduce climatic variations for both physical and biogeochemical variables simultaneously. We will carry out novel analyses concerning the vulnerabilities of the ocean carbon sink to climate change and emission pathways, taking also into account the probability density function for such vulnerabilities using Monte-Carlo ensemble simulations (WP3). A series of longer “stabilisation scenarios” will be carried out in order to quantify the long-term effect of specific emission scenarios, with special emphasis on holding climate change and atmospheric CO_2 concentration at bay (WP3).

Considerable regional ocean carbon sink strength variations: Any modelling of the variable ocean carbon sources and sinks will be futile without corresponding observations from the real world. We will, therefore, build on the observations and data syntheses carried out under the successful FP6 *Integrated Project* CARBOOCEAN, and extend these highest accuracy data sets for the most vital oceanic regions North Atlantic Ocean, Tropical Atlantic Ocean, and Southern Ocean (WPs 4 and 5). The new focus on the Tropical Atlantic Ocean was selected because of the huge buffering capacity of the warm surface waters, which then are transported poleward and undergo significant alterations as preconditioned water masses to be transported downward at high latitude deep water production areas. The tropical preconditioning with respect to CO_2 can be decisive for the apparent sink strength changes at higher latitude. These new data sets will be directly used in the model data integration (WPs 6 and 7). Further these data collections serve as test bed operations for the emerging partners of the European Research Infrastructure ICOS (stakeholder’s handbook: Ciais et al., 2009, website: http://www.icos-infrastructure.eu/). The new data sets will be essential to answer the question on whether the transient declines in ocean carbon sink strength in the classical high human-produced CO_2 storage areas North Atlantic and Southern Ocean are only transient or whether they reflect a trend which could potentially indicate a dangerous overall decline in ocean carbon uptake capacities which may have been overlooked before. A dedicated detection analysis will be carried out with stand-alone carbon cycle models forced by synoptic (daily re-analyses) atmospheric data in order to determine the threshold beyond which the CO_2 air-sea-fluxes start to show a clear signal which can be attributed to human-induced climate change and not to natural variability (WP3).

Physical and biogeochemical feedback processes: The identification of physical and biological as well as biogeochemical processes which govern the oceanic carbon source/sink distribution plus the appropriate representation and quantification of these processes in Earth system models is a difficult and quasi-persistent challenge for both measuring and modelling scientists. Processes controlling the vertical distribution of dissolved properties and hence air-sea exchange of CO2 are referred to as C pumps (Volk and Hoffert, 1985). Our main objective is to improve the capability of large scale ocean C cycle models to reproduced observed variability of the ocean C cycle and forecast its future evolution rather then the detailed description of marine ecosystems. Accordingly, we select a small number of key processes for the “biological carbon pumps” (WP1) and the “physical carbon pumps” (WP2), synthesise the knowledge available from observational studies, and implement respective formulations in the models. For the biogeochemical processes relevant to the carbon cycle climate model these processes are: Changing remineralisation rates and organic matter sinking speeds as a function of warming and increasing pCO_2 (decreasing seawater pH value), changes in the fate of the vertical particle flux due to changes in ecosystems and their community structures, and the advection of important carbon sources and sinks from continental margin areas (WP1). In WP2, the physical key processes for the carbon cycle climate feedback of changing overturning circulation under climate change and of changes in sea ice cover will be addressed. We will systematically establish whether ocean pCO_2 can be used to monitor changes in the overturning circulation, as small changes in dissolved inorganic carbon due to such circulation changes would map significantly enlarged on the surface ocean pCO_2 pattern. The results from process studies will be significant as input to WP6 on the systematic model calibration for the selection on model parameters, which will be used in the optimisation. All climate models to date have a quite coarse resolution due to the immense computational demand of these models. In order to establish a better knowledge on what we might miss in respective coarse resolution model scenarios on the ocean carbon sink, we will carry out a study on the role of oceanic eddies for air-sea CO_2 fluxes in relation to wind-stress. For this study we choose the Southern Ocean, as one of the key areas for changes in the ocean carbon sink, which is critical to correct parameterisations of the horizontal and vertical mixing processes and has proven in the past to react sensitively to climate change induced alterations of the wind-field (e.g., Toggweiler et al., 2006; Lenton et al., 2009) (WP2). The skill score metrics for performance assessment of model computations with respect to measurements (WP7) will be employed to establish whether the improved process parameterisations indeed result in an improved reproduction of the changing ocean carbon sink.

Observing systems: With respect to the European Research Infrastructure ICOS, which should be the European back bone for marine carbon cycle observations, the European ocean carbon observing systems will be further developed and extended. As an overall appropriate carbon observing system is a huge task, which by no means can be developed or maintained through selected single research projects, we focus here on a series of key elements which deserve a European concerted effort. These elements will significantly contribute to establish improved European monitoring capabilities. For the surface ocean a coordinated effort on combining VOS lines, buoy data and in-situ measurements from research vessels will be enabled, which will deliver cutting edge data on the evolution of air-sea CO_2 fluxes over the North and Tropical Atlantic as well as the Southern Ocean (WP4). Such a new coordinated approach is necessary in order not to loose the momentum on data quality and standardisation as achieved through previous research projects, and to merge European carbon data initiatives into a coherent framework, which is currently not carried out in any other international network. For the deep ocean, both extended deep section data but also data from time series stations or reoccupied stations at important choke points will be collected, analysed and synthesised (WP5). The key question of the vulnerability of the ocean carbon storage process over time with respect to climate change will be addressed jointly by WP 3, WP5, and WP7. The data sets from WP2, WP3, WP4, and WP5 will be systematically exploited by WP6 on model calibration and WP7 on model-observation comparison. In WP8, key work on the synthesis of existing and emerging data sets on ocean carbon cycling will be carried out, which will lead to new cutting edge data products as needed for ground-truthing any serious attempt to simulate and predict the ocean carbon sink over time: a merged 3-D carbon data product of the CARINA and GLODAP data sets, a new release of the SOCAT data set, and new atmospheric data from VOS lines and other vessels carrying automated systems.

Model developments and combinations of models with observational data: We will make an integrated effort on systematically improving ocean carbon models with respect to observations using different methods. As this is a newly emerging field, we pursue such a diverse approach rather than to calibrate only one model system. The experiences obtained from different model concepts and calibration/assimilation procedures will give us the framework at hand to approach systematic calibration of entire coupled Earth system models for the next several years to come. In order to bundle the different approaches we will carry out the following systematic model calibrations (WP6): A calibration of the MICOM biogeochemical ocean model which also used in the Norwegian Earth system model NorESM using the sequential Ensemble Kàlman Filter method, where we will focus on the impact of model physics on the ocean carbon cycle (link to WP2) and selected optimisations of biological pump relevant parameters (link to WP1). We will use the adjoint method as a variational method to optimise systematically the biogeochemical model parameters in the biogeochemistry model of the MITGCM. The optimised ocean biogeochemistry will then be used in the MIT/CCDAS optimal coupled ocean-land-carbon cycle model to determine the impact of improved ocean carbon cycle on terrestrial CO_2 fluxes and vice versa. As the computational demand for data assimilation procedures is huge, we will further use an Earth system model of intermediate complexity (Bern-3D-model) using also the Ensemble Kàlman Filter approach, but with a quantitatively much larger possibility for runs and over longer time periods. A current problem in Earth system modelling is the long integration time which is required for ocean models (physics and biogeochemistry) in order to achieve quasi-equilibrium (ocean turn over time is of the order of 1000 to 2000 years). For testing the models' ability to reproduce a drift free quasi-equilibrium also for the oldest parts of the world ocean's water masses, the time efficient tracer transport matrix method (Khatiwala, 2007; Merlis and Khatiwala, 2008) will be employed for several biogeochemical ocean models and different flow fields in order to calibrate first order governing parameters for optimal pre-industrial start fields of scenarios. Finally, we will pursue the variational calibration of the PISCES biogeochemistry model with biogeochemical observations from individual sites and satellite products in order to also calibrate more complex ecosystem model parameters in the selection of models within this project. For the calibration and integration of the models with data, the newly emerging data from WP2, WP4, and WP5 as well as the methodology for model performance assessment from WP7 will be needed.

Outreach to policy makers:
Recently, a number of promising report products for policy makers have emerged (*IPCC 4th assessment report* – IPCC, 2007; *Integrated assessment of the European and North Atlantic Carbon Balance* - Schulze, Heinze, et al., 2009; policy briefs such as UNESCO-SCOPE-UNEP, 2009; *special report by the German Advisory Council on Global Change* – WBGU, 2006; and The Copenhagen Diagnosis, 2009), on which we will build to provide further direct firsthand information for policy makers on the evolution and significance of the ocean carbon sink. We will compile annual updates on the altering ocean carbon sources and sinks and their drivers on a regional as well as global basis. We will summarise the ocean state with respect to carbon cycling as well as the vulnerability of the ocean sink for human-produced CO_2 for policy makers, decision makers, and other end-users, e.g. the research communities on ocean acidification, environmental agencies such as the European Environmental Agency (EEA), global observing systems, and large international core projects such as IGBP SOLAS, IMBER, GEOTRACES, European FP7 projects such as EPOCA (on ocean acidification) and COMBINE (on new components for Earth system models) and further programmes.

B.1.3 S/T methodology and associated work plan

B.1.3.1 Overall strategy and general description

For this large scale integrating project we pursue a strategy which enables a broad enough scope to tackle the problem of changing ocean carbon sources and sinks from every necessary angle, but at the same time interlinks all components in order to achieve an overall integration among the different components. We place particular emphasis on the integration of modelling and observations and wherever advisable combine modelling and measuring scientists in each work package. The strategy of the work plan follows directly the requirements of the call.

The work on processes and feedbacks is carried out under core theme 1 using three work packages (see Figure 1.3.3) which are dedicated to the identification and quantification of key processes in the fields of biology and biogeochemistry (WP1), quantification of key physical processes (WP2), as well as the realisation of future scenarios including analyses on vulnerabilities and climate stabilisation (WP3). The time line for the work in WP3 is tailored to provide input to the next IPCC report and a first set of scenario runs is completed within the first six months.

For practical reasons, we have assigned the observations - as base line information for all other WPs and CTs - together in one core theme (CT2) and work packages 4 and 5 (see Figure 1.3.3) in order to achieve a best possible coordination of the measurement programme. The observations are then firmly linked with all other components of the project. The observations feed into the process work packages 1 and 2 as foundation for the derivation of key processes on the ocean carbon cycling, into WP3 for an accurate as possible quantification of feedback processes as well as carbon sink vulnerabilities under changing climate and changing CO_2 concentrations using future emission scenarios, into the model calibration and model assessment work packages 6 and 7 as real world reference data, into the synthesis work package 8 for deriving best integrated estimates on ocean-atmosphere carbon exchanges, and of course WP9 on data management, where all data is archived and disseminated.

The integration of models with observations will be systematically pursued under CT3 in WP6 and WP7 (see Figure 1.3.3). WP6 will carry out systematic model calibrations using different approaches with the observations provided through WP4, WP5, WP8, and WP9 as input. In WP7, a rigorous comparison with observations of the models used in WPs 3 and also 6 will be accomplished. WP7 also will develop the skill score metrics (standardised measures for the discrepancy between model results and observations), which will be applied in WP6 for assessing the quality of model results and for systematic calibration of the ocean carbon cycle models and the Earth system models. The results of CT3 are a prerequisite for the improved synthesis on carbon sinks in WP8. This work requires a long-term commitment dedicated to provide updated knowledge on sinks also after the completion of the next IPCC report.

The overarching work packages WP8, WP9, and WP10 cut across all core themes and therefore have no governing core theme. The project coordinator and the deputy coordinator will steer these work packages together with the leaders of the overarching WPs, so that best possible overarching integration of all disciplines and science work will be achieved. WP8 is dedicated to synthesis work on the ocean carbon sources and sinks. It will take care of important synthesis for observational data sets, will provide global and regional air-sea CO_2 flux numbers for separate years, and will transmit all key results of the project to policy makers and other stakeholders of the climate change topic. WP9 will carry out the professional data management which is needed to archive the project's long-term results and disseminate them to the science community and the end users. The data management will also include the management of model results.

Overarching work package 10 on consortium management will achieve a smooth project flow through continuous following-up, review, and assessment of progress in the various WPs and CTs. It will provide support for the outreach to policy makers. WP10 further will coordinate all scientific as well as administrative work, communicate between all governing and executing levels of the project, will organise project meetings, and compile the periodic reports. Following the call for this project, we have placed a somewhat minor emphasis on training aspects, though we expect that a series of PhD students will be trained in CARBOCHANGE. Also we will not explicitly include a training programme for secondary schools (as done under CarboEurope and CARBOOCEAN). This does by no means that we do not think that these aspects are of extreme importance, but we rather see that the training aspects are to a high degree already addressed by running and emerging Initial Training Networks on ocean carbon cycle aspects and outreach projects on general global change issues. We aim at directly linking CARBOCHANGE to these training and outreach projects and to supporting them with any information and action which will be appropriate and helpful.

General description of the work packages

We describe now briefly the **rationale** behind the various work packages (WPs). The objectives, tasks, deliverables, and milestones associated with each WP are given in detail in the WP tables further below.

WORK PACKAGES OF CT1 - Key processes and feedbacks, future scenarios, and vulnerabilities:

WP1 Biogeochemical processes and feedbacks: lead Völker & Gonzalez

Next to physical processes, the surface ocean CO_2 concentration depends on the biological carbon pump. Global warming, ocean deoxygenation, and ocean acidification will affect the rates at which organic matter, opal, and $CaCO_3$ will be remineralised/dissolved as it sinks through the water column, leading to changes in the associated length scales. Recent work by Kwon et al. (2009) showed a surprisingly large sensitivity of atmospheric CO_2 to very modest changes in the remineralisation length scale of organic matter. The export of this organic matter from the surface ocean is the decisive element controlling the efficiency of the biological pump, which is the important quantity controlling the impact of ocean biology on the air-sea partitioning of carbon. It has been hypothesized that plankton community structure is essential in determining the fraction of production that is being exported to depth. However, this is far from well established, particularly since the relationship between the magnitude of carbon export and community structure is poorly understood. The continental margins and high-productivity areas associated with upwelling regions play a major role supplying organic carbon and nutrients to the open ocean that influence the air-sea CO_2 balance, which can lead to downstream productivity and respiration changes. However, very little is known about this potentially important interaction of the coastal and open oceans. We propose to test the high atmospheric CO_2 sensitivity in a comprehensive ocean carbon cycle model and to develop an understanding of what controls this high sensitivity, to study the role of primary and secondary producers for export strength and to investigate the interaction between coastal and open ocean by addressing the roles of the offshore transport of OC and nutrients on the carbon cycle in the Atlantic Ocean.

WP2 Physical processes and feedbacks: lead Anderson & Oschlies

The transport and mixing of water which carries anthropogenic carbon into deeper layers of the ocean is key for governing the speed of CO_2 uptake by the oceans. Up to now the uptake of anthropogenic CO_2 (C^{anthro}) by the oceans has been estimated based on the assumption of a steady state situation where ocean ventilation has occurred under constant conditions when it comes to degree of CO_2 saturation as well as for tracers, e.g. CFCs, used in the calculations. However, we have now reached a state where climate change has impacted the ocean physics that has changed the basis for the calculations of C^{anthro} making it necessary to develop better tools for these estimates. Examples of changes inferred from observations include changes in winter mixed layer depths in high and mid latitudes, changes in wind-induced upwelling in the eddy-controlled Southern Ocean, an area of substantial intermediate water formation, and changes in the sea ice coverage in the Arctic Ocean that, in turn, change the preconditioning of the waters that ventilate the Nordic Seas and contribute to the overflow to the North Atlantic and, eventually, the meridional overturning circulation. Furthermore, changes in seasonality may feed back on the net oceanic carbon uptake. For example, the decreased summer sea ice coverage in the Arctic Ocean promotes a larger than historic sea ice production during the winter season which result in a more intense brine formation that support ocean ventilation and oceanic uptake of atmospheric CO_2. All of the above changes in the physical environment affect the oceanic CO_2 uptake. Processes involved occur on scales smaller than those resolved by current carbon-climate models and therefore require parameterizations adequate for a correct representation of physical feedbacks. Within this WP we propose to use a hierarchy of models: Regional process models of sufficient resolution will be employed to explicitly resolve the relevant processes and to develop improved parameterizations for coarse-resolution models. The improved parameterizations will be used in carbon-climate models to investigate the large-scale impacts of local processes on oceanic CO_2 uptake.

WP3 Future scenarios under different emission curves and vulnerability analysis: lead Bopp & Totterdell

All modelling studies using coupled climate-carbon models (including those undertaken in the framework of EU FP6 *Integrated Project* CARBOOCEAN), have found a positive climate-carbon feedback in the 21st century (e.g. Friedlingstein et al. 2006). The uncertainty in this feedback, assessed by comparing the different models, is large. Nevertheless, these modelling studies point towards the Southern Ocean and the North Atlantic as key regions for explaining the simulated ocean contribution to this positive feedback. But the detailed processes (physics, biological) beyond the simulated response of the ocean carbon flux to climate change remain unclear. How would the simulated ocean response change for different emissions / concentration curves over 2000-2100 (especially for the new IPCC RCP scenarios)? How would the identified positive feedback evolve under longer-term simulations (2000-2300 or 2500)? At the same time, (some) recent observations and ocean-only simulations attest of a slowing down of the net carbon uptake by the ocean, which has been suggested to be caused by climate change and/or climate variability (e.g., Le Quéré et al., 2007; Telszewski et al., 2009). Is climate change already impacting air-sea carbon fluxes? If not, when will this impact be unambiguously separable from decadal variability? We will assess the uncertainty in future ocean uptake due to different model structure by comparing the response of the different models to future changes with an emphasis on mechanisms. Complementary to this, output from WP3 models for the historical period will be assessed with respect to observation-based metrics in WP7 to produce multi-model average projections. We will also assess the uncertainty in future ocean uptake by focusing on the parameter uncertainty. Many models can fit the historical record with roughly similar accuracy (as that is mainly determined by solubility and circulation) but over longer century time-scales the biogeochemical feedbacks will come into play and will give a range of possible uptakes. Techniques are available to explore the probability density function (PDF) of future atmospheric CO_2 and temperature change, and can be used to determine the PDF due to variations in biogeochemical parameters that fit the historical record. This approach is complementary to the calibration in WP6 because for many parameters the optimal value is not precisely determined by historical data but the resulting uncertainty in future predictions is large. The work of WP3 is tailored in such a way, that it contributes directly to the 5^{th} IPCC assessment report.

WORK PACKAGES OF CT2 - Observing system of ocean carbon changes :

WP4: Surface observing system: lead Schuster & Boutin

In the **N. Atlantic and Tropical Atlantic**, we have a prototype of an effective and accurate observing system following CARBOOCEAN, which operated during the period 2005-2008. We will build on this prototype, improving its efficiency and continuity of operation with the aim that it should deliver results as good as in its first year of operation (2005). In subsequent years, there were periods when the performance of the observing system was reduced, due to its vulnerability to data gaps caused by equipment failure or by the uncertainties of the shipping industry. To make the system fully robust, a more co-ordinated approach is required. This will enable rapid response to equipment problems, and to the sometimes rapidly changing routes of commercial vessels. More traceable and more frequent cross-calibration of the observing system is also desirable, as is improved accuracy of atmospheric measurements on the observing vessels, which would potentially enable their use in atmospheric inversions. Useful in-water oxygen measurements should also be possible given improved sharing of expertise and equipment across the network. A co-ordination unit will be initiated to provide this extra level of support.

In the **Southern Ocean** we cannot hope to have the density of coverage possible in the Atlantic. However the repeated transects of research vessels will enable a decadal picture to be built up in the Atlantic, Indian and western Pacific sectors. We will prioritize synthesis of seasonal and decadal trends. No such synthesis presently exists, nor is one planned under CARBOOCEAN We will also undertake studies characterizing the variability captured by drifters in the Southern Ocean, that suggest variability is under-sampled by ship observations. In particular a better understanding of the physics and biology driving the high frequency variability may help to improve the design of monitoring systems.

In the **European coastal** seas, we will encourage similar efforts, while recognizing there is insufficient funding available to fully support them all from this call. Because of these limited funds, observations in coastal seas are not directly supported in this proposal, but we will link with national efforts supporting coastal observations, to provide an international, regional-to-global framework to make a co-ordinated network of disparately funded observing programs.

In **the atmosphere**: we will undertake precision observations of atmospheric CO_2 and oxygen/ nitrogen designed to enable us to test out the use of regional patterns of atmospheric potential oxygen as independent method of observing air-sea carbon fluxes over large regions, and to enable us to integrate our findings with atmospheric and terrestrial studies .

Marine and atmospheric pCO_2 measurements will be calibrated using gases traceable to WMO standards. Marine pCO_2 observations should normally be accurate to within 1 uatm, and special attention will be paid to the determination of equilibtrator and seawater temperatures which have in the past been shown to be significant sources of error. Building on practice established in CarboOcean, we will ensure that all partners are using compatible schemes for the reduction of raw data to obtain pCO_2 values and fluxes. For CARIOCA sensors, a check of the calibration is made by comparing ship and mooring measurements when the instruments are deployed and recovered. In addition, CARIOCA pCO_2 sensor measures optical dye absorbance at three wavelengths, ensuring an internal control of the calibration of the CO_2 sensor (Copin-Montegut et al. 2004).

WP5 Deep ocean, time series, choke points: lead Rios & Hoppema

WP5 will undertake carbon-related measurements on carefully selected **hydrographic sections** where these contribute to closing carbon budgets for the Atlantic Ocean. Priority will be given therefore to observations that enable assessment of the change in the inventory of anthropogenic and natural carbon in critical regions and in transport across choke points. Time series stations at choke points complement the deep sections by allowing an assessment of high frequency processes and mechanisms. Many/most of the sections and time series have been occupied in the past. The formation regions of water masses (in the Labrador Sea, the Irminger Sea, the Iceland Sea, and the Southern Ocean) are considered of particular importance, as they allow an assessment of the interannual and decadal changes in anthropogenic carbon uptake.

The hydrographic sections include 75ºN, a trans-Arctic section, a Greenland-Ireland section, a Greenland-Lisbon section, a Labrador Sea section, and the Prime Meridian (0°W) section in the Weddell Sea. The time series stations are the Irminger station (64.3ºN, 28ºW), the Icelandic station where the changes are rapidly detected (68ºN, 12.66ºW), and the PAP (Porcupine Abyssal Plain) site (49ºN, 16.5ºW). The flow of the lower limb of the Meridional Overturning Circulation (MOC) from the North Atlantic Ocean to the Southern Ocean is a critical transport pathway for natural and anthropogenic carbon. Sections for assessing the changes in anthropogenic carbon inventories and budgets are the sections along 24ºN, 8ºN, and the Prime Meridian (from 52°S to Antarctica) and a north-south section along the western South Atlantic Ocean (from French Guyana to Ushuaia). Complementary data exist on the Drake Passage between South America and the Antarctic Peninsula. Another choke point is the Strait of Gibraltar which is a key site for crucial exchanges of water, salt, and carbon between the North Atlantic Ocean and the Mediterranean Sea.
In addition, one hydrographic section and three time series stations are located in the eastern Atlantic Ocean in order to assess the carbon changes in this important upwelling area where the biochemical processes are affected by natural and anthropogenic carbon changes. The time series stations along this eastern boundary are ESTOC (29ºN, 16ºW) near the Canary Islands, TENATSO (16ºN, 24ºW) near the Cape Verde Islands, and PIRATA (6ºS, 10ºW) situated in the Tropical Atlantic Ocean. The hydrographic section along 28ºN from 12º to 14ºW will be carried out four times per year.

Carbon measurements will be conducted with state of the art methods, e.g., coulometry for DIC and high precision potentiometric titration for alkalinity. Consistency between cruises will be achieved by applying internationally recognized certified reference material, obtained from Prof A. Dickson (Scripps Institution of Oceanography), and performing consistency analysis using the quality controlled data from the GLODAP and CARINA synthesis products. WP5 will advance the synthesis of the subsurface carbon, nutrient and oxygen data bases to the point where these products are available for use in modelling studies, to provide the best possible.

WORK PACKAGES OF CT3 - Data model integration:

WP6 Systematic model calibration using observational data: lead Bertino & Scholze
WP6 will construct and operate a suite of modelling systems that use a range of oceanic observations for systematic calibration of the physical and biogeochemical process parameters (constants used in the process descriptions) of a set of stand alone ocean models and an EMIC, plus a system that can calibrate the ocean model simultaneously with a terrestrial biosphere model by using observed atmospheric carbon dioxide concentrations (in addition to the oceanic observations).The systems will build upon a set of models covering time scales from decadal to millennial (MICOM-HAMOCC, MITgcm, Bern3D model) and apply two different advanced data assimilation methods for calibration: Ensemble Kàlman Filter (EnKF), a sequential method, and the adjoint method, which belongs to the variational methods. Observational constraints will include T, S, concentrations/partial pressures of carbon, nutrients, CFCs, radiocarbon, potential alkalinity, and remotely sensed ocean colour. Data will be provided by CT 2 and existing data bases such as SOCAT, CARINA, or GLODAP. We will closely collaborate with WP9 on data management for the preparation of the best available input data sets for the assimilation procedures. Selection of observations, specification of uncertainties for definition of misfit functions (metrics), and interpretation of the results will be carried out jointly by observationalists and modellers. The WPs main deliverables are (i) consistency checks of multiple data streams and modelling concepts, which -as input to CT2- helps to improve process understanding (ii) calibrated systems to be used in WP8 for global syntheses that combine the information for observations and models in an optimal way and in WP3 for future scenario calculations. The new knowledge obtained will feed into international assessments and into a new class of coupled calibrated Earth system model frameworks to be developed in the coming decade.

WP7 Data-model and model-model comparison: lead Orr & Tanhua
Many work packages of this project rely on models, both Earth System Models and forced ocean models, as fundamental tools to assess ocean carbon sources and sinks. In these Workpackages (WP1-3, WP6, WP8) models will be used to assess the modern mean state and its variability as well as how these conditions have changed in the past and will change during the 21st century and beyond. Models will also be used to diagnose controlling processes and ocean carbon-climate feedbacks. Yet models are biased. They must be evaluated to assess how well they agree with real data so that we can assign some level of confidence to their projections. In WP7 we will use the best observational data sets available of carbon and related tracers to evaluate the accuracy of the simulated mean state, seasonal variability, and interannual variability at the regional and global scale in the relevant models used in this project. Regional analyses will focus primarily on the

Southern Ocean, the North Atlantic Ocean, and the Arctic Ocean. Particular emphasis will be placed on assessing the extent to which models represent observed changes in North Atlantic and Southern Ocean air-sea CO_2 fluxes (CT2). Global and regional data will be used as targets to quantify model-data agreement. With these data constraints, we will assign model performance indices, and these will be used together to provide best "weighted" projections. Simultaneously, we will asses the extent to which skill scores for different time scales (mean states, seasonal variability, and interannual-to-decadal variability) are correlated across models and can or cannot be used to legitimately weigh future projections. We will also use the range of model results in combination with the best estimates to provide statements regarding the precision and accuracy of model projections and to assess consistencies in carbon-climate feedbacks. Furthermore, we will strive to attribute anthropogenic trends in the data based on the consistencies of trends in modelled carbon and related tracers.

OVERARCHING WORK PACKAGES:

WP8 Global synthesis and outreach to policy makers: lead Le Quéré, Olsen & Bakker
WP8 will work with all Work-packages to synthesize the information produced within CARBOCHANGE, both from data collection and modelling, and provide products that can be used by other scientists, students, policy assessments, press agents, and the public.
WP8 will work towards the establishment of *annual* releases of policy-relevant information on the state of the marine carbon cycle. These releases will be based on annual updates of at least five models forced by increasing atmospheric CO_2 concentration and changes in climate, which will provide the mean annual sink and a measure of the additional uncertainty estimated from the model spread (as in Le Quéré et al. 2009). The level of confidence in the model results will be determined using the updates of the Surface Ocean CO_2 Atlas (SOCAT), also released also by WP8.
WP8 will also create a global 3-dimensional Atlas of key carbonate variables. This information is needed by a wide group of people, particularly those working on the impacts of ocean acidification, and to validate ocean models. WP8 will merge the GLODAP and CARINA datasets into a unified, consistent dataset, and use this product and other available data to assess the export of carbon and $CaCO_3$ to the deep ocean, and provide the global distribution of ocean DIC, TA, pH and $CaCO_3$ saturation states. Using existing data, a global adjoint model will be applied to quantify monthly CO_2 air-sea fluxes and carbon export fluxes. This is the first time that such analysis will be done with a monthly resolution, thus allowing exploration of processes driving their seasonal cycles.
The activities of WP8 will be complemented by a report on the vulnerability of the oceanic CO_2 sink and a summarising outreach paper in a suitable journal including high latitude CO_2 fluxes and the response of the oceanic CO_2 sink to climate change. The annual releases of new global as well as regional carbon flux numbers will be accompanied by co-ordinated press releases among CARBOCHANGE partners and with the Global Carbon Project, and will include material for the press, pictures and a summary for a lay audience. The SOCAT and 3-D atlas data products will be accessible through a Live Access Server from PMEL. The model results will be maintained by the UEA and accessible through a web server. Both data and model products will be visible from the web sites of CARBOCHANGE, the Global Carbon Project and IOCCP, which are popular web sites for carbon research.

WP9 Data management: lead Schlitzer & Pfeil
The sharing of data and information among partners of large coordinated projects, such as CARBOCHANGE, strengthens the collaboration between different disciplines and research groups and ultimately leads to an increased scientific output through synergistic effects. The benefit of CARBOCHANGE to the wider scientific community also requires data generated within the project to be freely available and easily accessible. To encourage and promote data and information exchange in a timely and efficient manner, CARBOCHANGE will establish a data policy with binding rules for all project partners. While calling for openness and free flow of data between partners, these rules must also protect the intellectual property rights of the data producers (link to the EU FP7 coordination action COCOS). CARBOCHANGE will also set up a cost-effective centralized data management infrastructure allowing data storage and data flow with minimal effort for individual scientists. Two major types of data will be handled: (1) direct measurements (e.g. water column data, subsurface measurements) and (2) model output. **Direct measurements:** CARBOCHANGE will employ a data manager (half time) at the coordinator's office who will be responsible for archiving data and making the metadata available on the project's website. Technical implementation will use the facilities of WDC-MARE (World Data Center for Marine Environmental Sciences, University of Bremen) for data storage and access. **Model output:** Output from the different

models employed in CT1 and CT3 will be stored and maintained in a common format at LSCE to allow easy access by PIs and to facilitate multiple model comparison and model-data evaluation. Model output differs greatly from observational data in terms of data storage size, logical file structure, and formats. Model output will therefore be maintained separately from observed data. However, efforts must also be made to facilitate comparison of model results to data that is acquired during CARBOCHANGE. A subset of CARBOCHANGE model output will be provided to LSCE (Partner 6) in a common netCDF format following the OCMIP-4 conventions taking advantage of LSCE's previous experience in building, storing, and distributing multi-model output in a common format during the OCMIP-2, -3, and -4 model comparison efforts (see OCMIP-4 archive guidelines at http://www.ipsl.jussieu.fr/OCMIP/phase4/simulations/OCMIP4/HOWTO-OCMIP4.html).

WP10 Management of the project: lead Heinze & project manager to be assigned/hired
WP10 is dedicated to all managerial aspects of the project (for details see section 2.1) and also will address important outreach issues. Management includes the items: Scientific management, administrative/financial management, communication between the European Commission and the coordinator as well as the consortium, internal communication within the consortium (including the scientific steering committee, the executive board, and the international advisory board), general coordination, supervision, accomplishment, and submission of periodic reports, solution of problems through addressing corresponding panels, general project dissemination/outreach to the scientific community and the general public, press contacts, review and assessment of project tasks, timely notification of partners on upcoming deadlines (deliverables, milestones, project meetings, reporting), updating of important project lists and archives (deliverables, publications, partner lists and addresses, email-lists), design, maintenance, and continuous updating of the project homepage on the internet. The scientific project manager will coordinate at least two outreach papers to policy makers together with the consortium. The project manager in concert with the project director (coordinator) and key PIs throughout the consortium (such as the CT leaders) will provide information packages, fact sheets, and press releases whenever appropriate and of promising impact. We will in particular explore most efficient pathways for the channelling of relevant information on the changing ocean carbon sink to policymakers in close collaboration with the scientific officer at the European Commission to ensure maximum impact of the new knowledge created by CARBOCHANGE. We will in particular forward any relevant new results to other projects and programmes for which ocean carbon cycling is of relevance such as projects on ocean acidification, development of Earth system models, carbon capture and storage, renewable and alternative energy production systems, and marine food production. A considerable part of the management person effort is dedicated to producing the scientific as well as financial periodic reports (the person effort has been included in the delivery of annual meetings).

B.1.3.2 Timing of the different WPs and their components

Year	**1**				**2**				**3**				**4**			
start month	**1**	**4**	**7**	**10**	**13**	**16**	**19**	**22**	**25**	**28**	**31**	**34**	**37**	**40**	**43**	**46**
end month	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**33**	**36**	**39**	**42**	**45**	**48**
WP1 Biochemical processes and feedbacks																
1.1. Organic matter remineralisation	■	■	■	■	■	■	■	■								
1.2. Vertical carbon flux, role of plankton	■	■	■	■	■	■	■	■	■	■	■	■				
1.3. Carbon export to Atlantic Ocean			■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP2 Physical processes and feedbacks																
2.1. Sea ice cover and deep-water formation		■	■	■	■	■	■	■	■	■	■	■	■	■		
2.2.Variability deep-water formation		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2.3. Variability in air-sea CO_2 fluxes	■	■	■	■	■	■	■	■	■	■	■	■				
2.4. Eddies, Southern Ocean		■	■	■	■	■	■	■	■	■	■	■	■	■		
WP3 Future scenarios, vulnerability analysis																
3.1 Vulnerability of sources and sinks	■	■	■	■	■	■	■	■								
3.2. Probabilistic distribution of vulnerability	■	■	■	■	■	■	■	■								
3.3. Stabilization	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
3.4. Detectability	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
WP4 Surface observing system																
4.1. Network for estimates of air-sea flux	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.2. Co-ordinate observational network	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.3. Surface water CO_2 - Atlantic	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.4. Surface water CO_2 - Southern Ocean	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.5. Collect CO_2 and O_2/N_2 data in the atmosphere	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.6. Variability of the air-sea flux of CO_2			■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.7. Seasonal sea surface pH Atlantic and Southern Ocean			■	■	■	■	■	■	■	■	■	■	■	■	■	■
4.8. Effect of high frequency variability on air-sea flux				■	■	■	■	■	■	■	■	■	■	■	■	■
4.9. Collaborate with WP8 with quality controlled data				■	■	■	■	■	■	■	■	■	■	■	■	■
4.10. Comparison atmosph. observations -in-water techn.				■	■	■	■	■	■	■	■	■	■	■	■	■

WP5 Deep ocean, time series, choke points																
5.1. Collect oceanic time series data																
5.2. Collect CO_2 along 10 predefined sections																
5.3. Variability of carbon storage at choke points																
5.4. Regional carbon inventories and changes																
5.5: Natural variability of carbon cycle in upper ocean																
5.6. Assess trends on ocean acidification																
5.7. Contribute quality controlled data to Task 8.3																
5.8. Link atmospheric to deep water CO_2																
WP 6 Systematic model calibration																
6.1. Calibration in stand alone isopycnic ocean model																
6.2. Calibration of ocean/ terrestrial biosphere model																
6.3. EMIC calibration																
6.4. Calibration of models for circulation fields																
6.5. Calibration of one dimensionial model																
WP7 Data-model, model-model comparison																
7.1 Global comparison																
7.2 Performance indices																
7.3 Links across timescales																
7.4 Feedbacks																
7.5 Attribution																
7.6 Deep-ocean evaluation																
WP8 Global synthesis and outreach to policy makers																
8.1. Prepare annual releases of air-sea CO_2 fluxes																
8.2. Release of the Surface Ocean CO_2 Atlas (SOCAT)																
8.3. Merge the GLODAP and CARINA datasets																
8.4. Report on vulnerability of the oceanic CO_2 sink																

WP9 Data management																
9.1. Observational data management																
9.2. Model output data management																
9.3. Information management																
9.4. Data management infrastructure																
9.5. Assistance in datasets and software optimisation																
9.6. Update of SOCAT input database																
WP10 Project management																
10.1. Internal communication																
10.2. Communication EC, coordinator, consortium																
10.3. Survey of project tasks and deadlines																
10.4. Supervision and submission of reports																
10.5. Addressing panels																
10.6. Dissemination and outreach activities																
10.7. Maintain and update project homepage																

B.1.3.3 Graphical presentation of the components showing their interdependencies (Pert diagram)

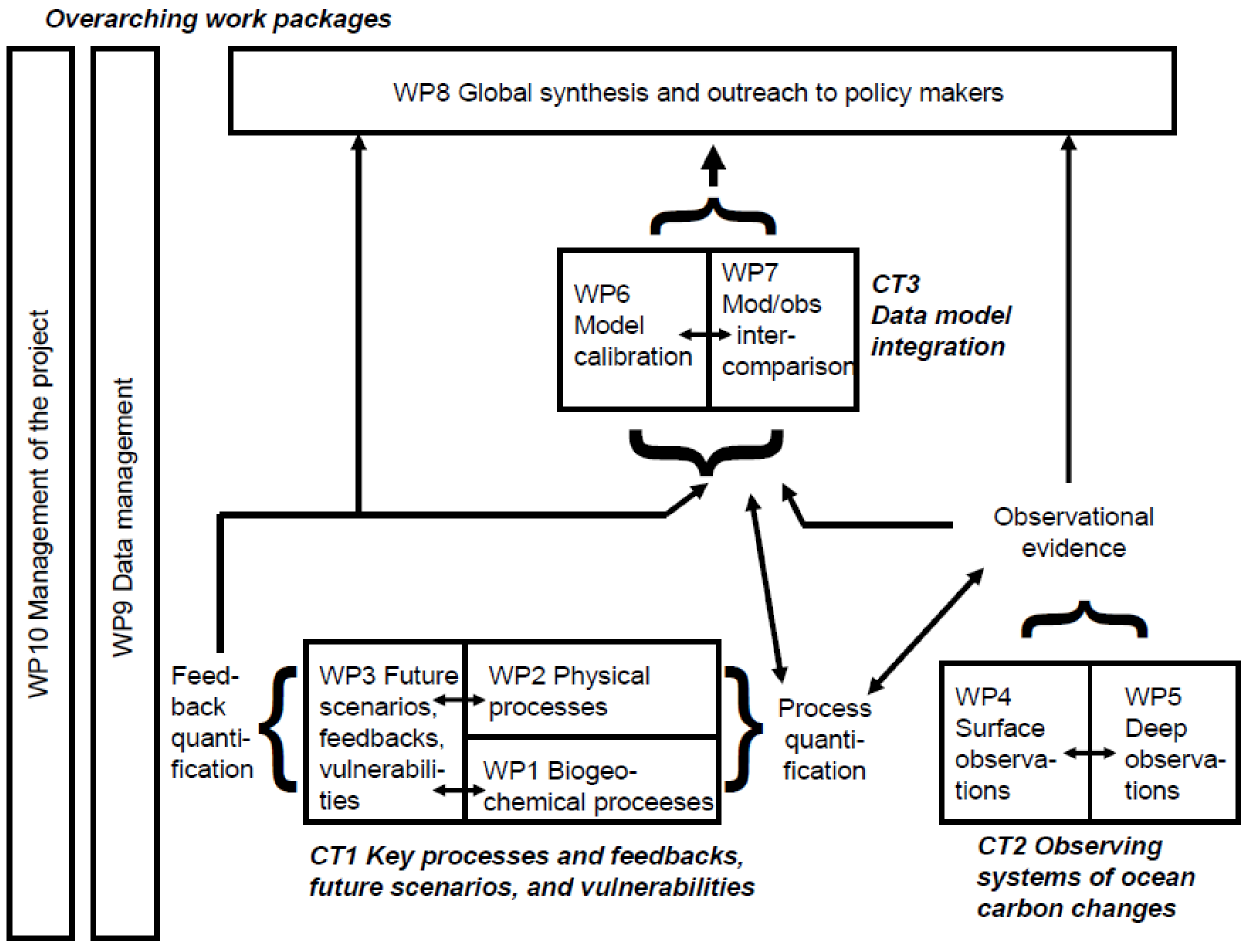

Figure 1.3.3: Overall strategy of the work plan and interdependencies/flowchart of the work packages.

B1.3.4 Description of significant risks, and associated contingency plans

The work in CARBOCHANGE was designed so that the key activities can be kept and carried out as planned – though with a somewhat minor ambition – if one or more tasks can not deliver in time their products and results. For the proposed work we see four risks, which all are balanced by respective preventive measures or contingency plans:

1. *Suitable personnel cannot be hired in time to carry out the work planned:* In order to find suitable personnel for the project tasks, we will announce open positions early and through the most efficient channels (national websites, EU websites, relevant scientific vacancy services such as "Earthworks") which have proven to work well in the past. We will try to attract additional funds from national sources for inviting promising candidates for job interviews in order to assign appropriate candidates with the ambitious tasks.
2. *Shiptime cannot be secured in time and voluntary observing ships are rescheduled:* Usually, shiptime on research vessels has to be booked several years in advance. Planned project work on research vessels, therefore, has to rely on already planned ship expedition time in its earlier phase and that appropriate ship time will be granted by national authorities in the later phase of the project. Also, commercial ships which carry autonomous measurement systems for surface CO_2 and atmospheric CO_2 measurements may be rescheduled or even put out of service by the ship owning company. Such changes usually can be solved by shifting the measurement systems to new ships. Respective additional costs can lead to some delays in putting the systems into operation again. As backbone data sets for data assimilation are available already, the lack of single cruise data sets will not endanger the data-model integration efforts as such, but occasionally will limit their impact for the most recent past. We expect that these potential deficiencies can be diminished by repeat computations towards the project end, if needed.
3. *Complex earth system models are not available as newest cycles due to delays in components taken care of outside of this project:* The complex Earth system models are the products of large research teams involving also personnel outside of CARBOCHANGE. In selected cases it can occur that newest ESM cycles are not available in time for the planned modelling tasks due to work on a component by other groups contributing to the same model, but are not involved in CARBOCHANGE. In order to keep the planned modelling work on track, we can in most cases use an already existing earlier model cycle. We would inform all ESM teams involved in the project early in time, that respective operational model versions will be needed at given points in time, so that the teams can prepare themselves optimally for the start of the project.
4. *Bottlenecks in available supercomputer infrastructure and supercomputer processing time:* CPU time (central processing unit time), huge core memory, and huge archiving space (disc, tape silos) are necessary for carrying out the modelling tasks with advanced Earth system models and higher resolution ocean models. Supercomputers and storage media are expensive infrastructures and have to be booked in advance by the modelling groups through their respective national procedures and agencies. We will reserve the relevant resources for processing and archiving on the national supercomputer facilities as soon as the proposal would become favourably evaluated and contract negotiations would be entered.

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