Project:
GEOCARBON

Project full title:
Operational Global Carbon Observing System

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1. Introduction

1.1 Short summary

The results of marine CCDASs (Carbon Cycle Data Assimilation Systems) have been evaluated against observations or alternative model products in order to make a judgment on the quality of the results for giving different CCDAS-products different weights in an overall assessment of air-sea CO_2 transport. Due to the limited observational carbon data base in the ocean, two weaknesses become clear: (1) The CCDAS results have to be compared with the same observational data which has been used for the optimisation of the model (data assimilation). (2) For some CCDAS no direct observational counterpart is being measured. There are large discrepancies between the different CCDAS results for air-sea CO_2 fluxes.

1.2 Rationale for this deliverable

Importance: The deliverable is important for making an overall assessment of air-sea CO_2 fluxes varying over time. When averaging over an ensemble of trajectories for ocean-atmosphere CO_2 fluxes, one would like to associate quantifications of low uncertainty with more weight than less uncertain quantifications.

Issue addressed: So far, computation of seasonally and interannually changing air-sea CO_2 fluxes has been mostly carried out with forward models, that predict these fluxes and associated biogeochemical tracer distributions in the ocean. We try here to make a statement about the reliability of air-sea CO_2 flux estimates as derived from data assimilation procedures. In respective ocean CCDASs models and observations were before systematically combined with observations to arrive at more realistic air-sea carbon fluxes than with less or not at all constrained models.

Fitting overall frame of project: The task summarised here is trying to make a judgement on the the reliability of the air-sea CO_2 flux estimates as carried out with CCDAS. This task fits into the synthesising phase of GEOCARBON and aims at making a best possible (at least a most reasonable) overall assessment of computed air-sea CO_2 fluxes by partially (or fully) excluding unreliable quantifications.

This deliverable contributes to the following overall goals of GEOCARBON:

● Provide an aggregated set of harmonized global carbon data information (integrating the land, ocean, atmosphere, and human dimension).

● Provide comprehensive and synthetic information on the annual sources and sinks of CO2 for the globe and for large ocean and land regions.

1.3 Problems encountered and envisaged solution

There have been no particular problems been encountered. Some difficulties lie in the nature of scarce data sets as described below.

2 Full description

We first determine the performance of the two ocean model based CCDASs with respect to observations (1. Using EnkF, a sequential method, and the MICOM-HAMOCC model, partners NERSC and UiB. 2. Using the adjoint method, a variational method, using the CMCC model; CMCC). Then we compare the results of the ocean model based air-sea CO_2 flux estimates with atmospheric inversions.

2.1 Assessment of ocean model based CCDASs with respect to pCO2

The NERSC CCDAS: NERSC and UiB used a low-resolution (100x116 horizontal grid points, 32 vertical layers) version of MICOM-HAMOCC5 (Miami Isopycnic Coordinate Ocean Model and Hamburg Oceanic Carbon Cycle) model, which is the ocean component of the Norwegian Earth System Model (NorESM) to conduct the experiments. The model was simulated off-line, forced by the observed atmospheric forcing fields from the National Center for Environmental Prediction (NCEP) reanalysis product. The monthly atmospheric CO2 concentration was adopted from the Global Carbon Project (Le Quere et al., 2013). For the observations, we applied the surface underway pCO2 data collection (monthly gridded) from the Surface Ocean CO2 Atlas (SOCAT, Pfeil et al., 2013). The data assimilation method used is a Gaussian anamorphosis extension of the deterministic ensemble Kalman Filter (Simon and Bertino, 2012). This method is based on the deterministic ensemble Kalman lter (DEnKF, Sakov and Oke, 2008) and consists in introducing changes of variables, called Gaussian anamorphosis functions, in order to realize the analysis step with Gaussian distributed transformed variables (Bertino et al., 2003). This method has been shown to be applicable in large systems (Simon and Bertino, 2009) and to efficiently estimate model parameters in nonlinear frameworks (Doron et al., 2011; Simon and Bertino, 2012). The assimilation was done only in the biogeochemical component of the coupled model, precisely the phytoplankton growth rate and the gas transfer velocity. The ensemble is made of 96 members generated in January 1988. An ensemble simulation (no assimilation) has been run for 10 years in order to spin up the assimilation. The assimilation of the SOCAT data started on 1 February 1998 and stopped on 1 January 2004. To produce the Taylor diagrams (**Figure 1**), we averaged the ensemble output among 96 members and during the time period 1999-2003. In our Taylor diagram, *Ref* refers to reference run which was not assimilated with the observation data; *As* refers to model runs which were assimilated with the observation data; *Obs* indicates the gridded monthly SOCAT dataset (weighted per cruise).

The CMCC CCDAS: CMCC used for their experiments, the NEMO3.4 OGCM in the ORCA2 global ocean configuration (Madec and Imbard, 1996), coupled with BFMv5 biogeochemical flux model (Vichi et al., 2007a,b), and the 3DVAR assimilation scheme OceanVar (Storto et al., 2011). The NEMO+BFM (PELAGOS) model is initialized as in (Visinelli et al., 2014). The physical component starts from a previous 25-years spinup where we repeated the year 1988 given initial conditions for temperature and salinity as in the climatological WOA (2009). The biogeochemical component is initialized with the GLODAP and WOA climatologies, with no initial spinup of the various variables. This choice was motivated by the fact that all biogeochemical components show a non-zero trend during spin-up, so that the length of the spin-up would affect the choice of the initial condition. In addition, in order to obtain realistic results, the initial conditions have to be chosen as closely as possible to available data. Since GLODAP provides climatological maps for DIC and ALK in units of mol/kg, and the BFM initializes these variables in units of mole/m^3, the water density has to be taken into account for the conversion. For the alkalinity, we decided to multiply the GLODAP climatology by the constant 1024 (the average water density in kg/m^3), while for the DIC we decided to perform two experiments, the former (Experiment A) in which we also multiplied the DIC climatology by 1024 kg/m^3, and the latter (Experiment B) in which we multiplied the DIC initial condition by a density equal to 1000 kg/m^3. We decided to report both these experiments, which are summarized in **Table 1**.

For each experiment, we performed three runs in which we assimilate various components:

- The control run CTRL is the PELAGOS simulation with no data assimilation.
- The physics reanalysis run TSREAN is the PELAGOS physics reanalysis (assimilation of T&S data).
- The reanalysis run REAN is the PELAGOS reanalysis (assimilation of T&S plus DIC and alkalinity data).

Runs cover the period January 1st 1988 - December 31st 2010, with spun-up physics and BGC at rest.

Table 1: Species for the initial conditions and the data assimilation used in the two experiments.

	Experiment A			Experiment B		
	CTRL	TSREAN	REAN	CTRL	TSREAN	REAN
Assimilation of T&S	No	Yes	Yes	No	Yes	Yes
Assimilation of DIC&ALK	No	No	Yes	No	No	Yes
GLODAP ALK * 1.024	Yes	Yes	Yes	Yes	Yes	Yes
GLODAP DIC * 1.024	Yes	Yes	Yes	No	No	No

Below, we show the Taylor diagram (**Figure 2**) for the pCO2 averaged over the global ocean for the period 1993-2010, compared to the SOCAT monthly dataset for the same period. Blue dots represent the runs in which both the DIC and ALK initial conditions are multiplied by the water density 1024 kg/m^3 (here Experiment A), while red dots indicate the runs in which only the ALK initial condition is multiplied by the water density 1024 kg/m^3 (here Experiment B).

Discussion of the Taylor diagrams:

The Taylor diagrams (for details, please, refer to Taylor, 2001) are based on the respective assimilation run and the observational SOCAT surface ocean pCO_2 data synthesis (Pfeil et al., 2013). We provide the following Taylor diagrams for each of the two ocean model based CCDASa:

(a) All available data (globe).
(b) Autumn and winter (SON, DJF; northern hemisphere).
(c) Autumn and winter (SON, DJF; southern hemisphere).
(d) Spring and Summer (MAM, JJA; northern hemisphere).
(e) Spring and Summer (MAM, JJA; southern hemisphere).

In general it can be stated that the model fit to observed pCO_2 data is still far from good in all cases. The distribution over the seasons and hemisphere is not too different within each model (with perhaps the exception of the southern hemisphere which is somewhat better reproduced in the southern hemisphere as compared to the northern hemisphere in the PELAGOS model). The difference between cases with and without data assimilation turns out to be relatively small. This may show one general difficulty in data assimilation for ocean carbon cycle models: Ocean time scales are long and spatial scales of motion are small as compared with the atmospheric circulation. Further, the equilibration time for the ocean surface with respect to CO_2 air-sea gas exchange is about 0.5 years. Therefore, either changes in in the ocean circulation or in biogeochemical parameters influencing the air-sea gas exchange (and pCO_2) imposed on models runs over only few years, may not lead to really strong improvements. Rather, probably long-term data assimilation procedures would have to be applied which render a vastly improved basic state and generally improved combined physical, biogeochemical, and ecosystem processes. Expected higher resolution models under development may contribute to further improvements.

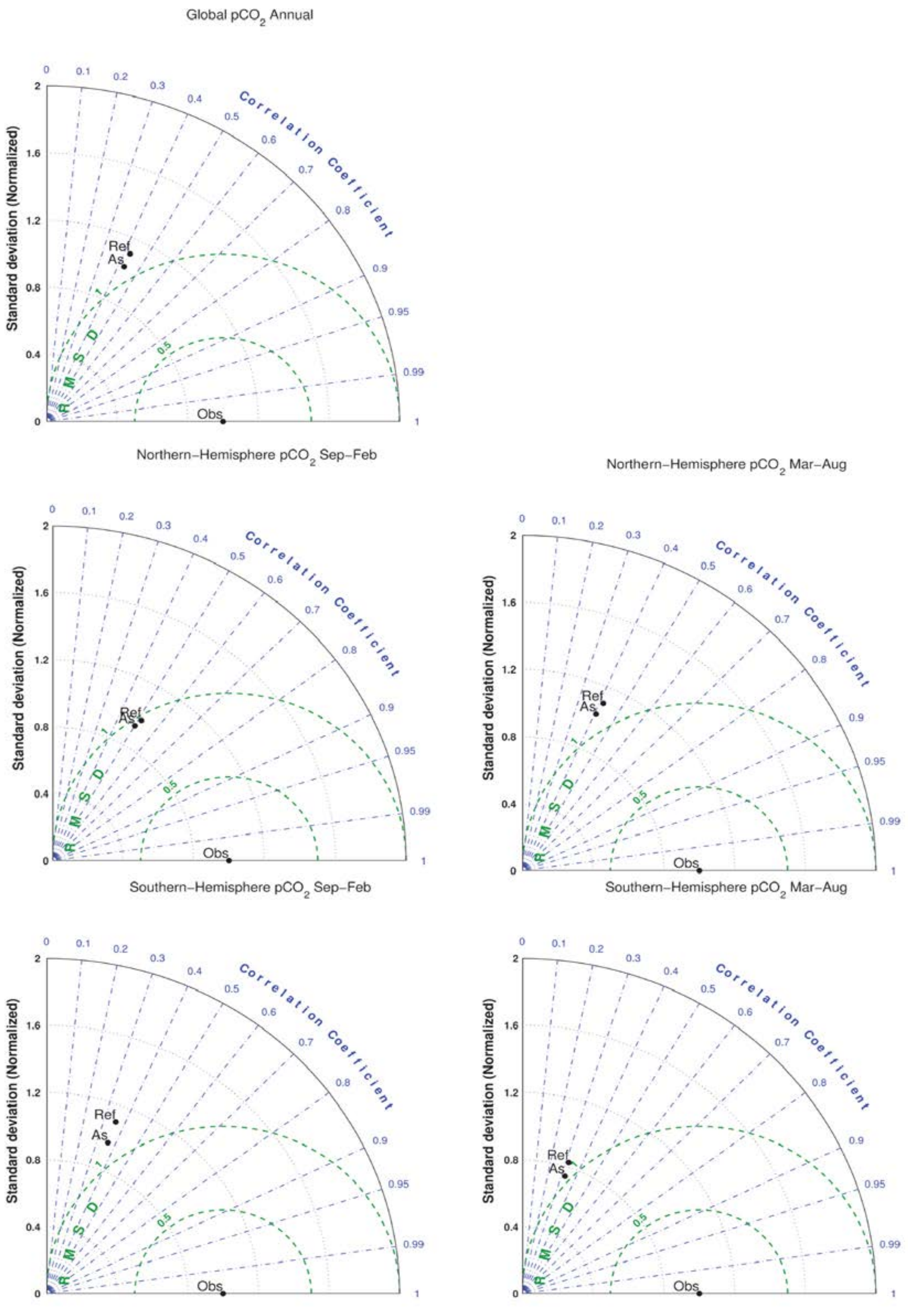

Figure 1: Taylor diagram for the MICOM-HAMOCC model hindcast.

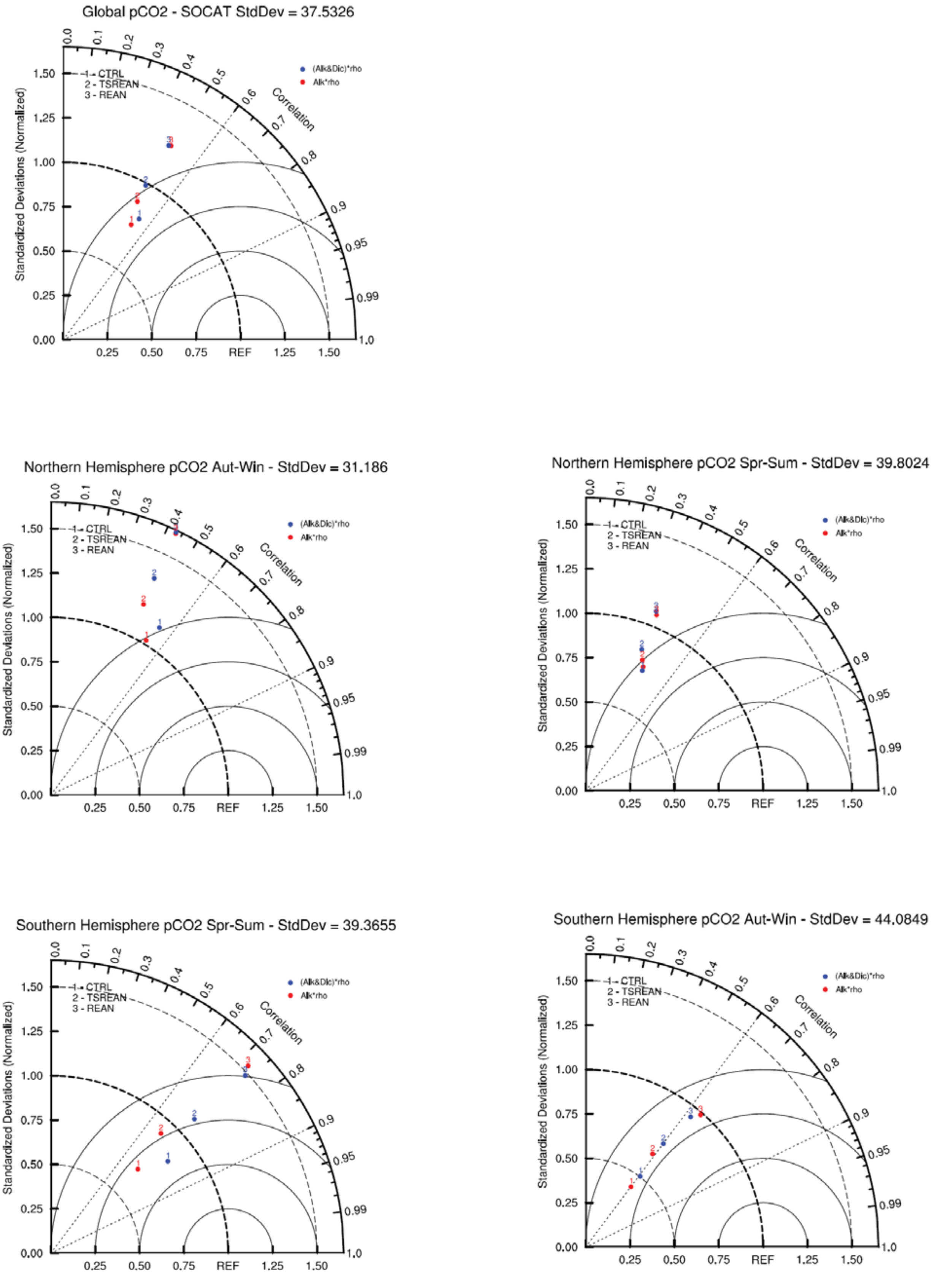

Figure 2: Taylor diagram of the PELAGOS model hindcast.

2.2 Assessment of atmospheric inversions in the context of other approaches

Van der Laan-Luijkx et al (GEOCARBON internal report) had compiled a comparison of atmospheric inverse optimisation using CarbonTracker with forward ocean models (without optimisation through data assimilation) as used for the GCP annual carbon budget update (Le Quéré et al., 2013)(**Figure 3**). Apart from the quite strong offset of about 0.5-1 PgC/yr between the inversions and the forward ocean models, it can be seen that the forward models show a smoother interannual variability than the inversions. The same holds for the interannual variability in the optimised ocean model runs using MICOM-HAMOCC (see deliverable D9.2, figure 2.4.2).

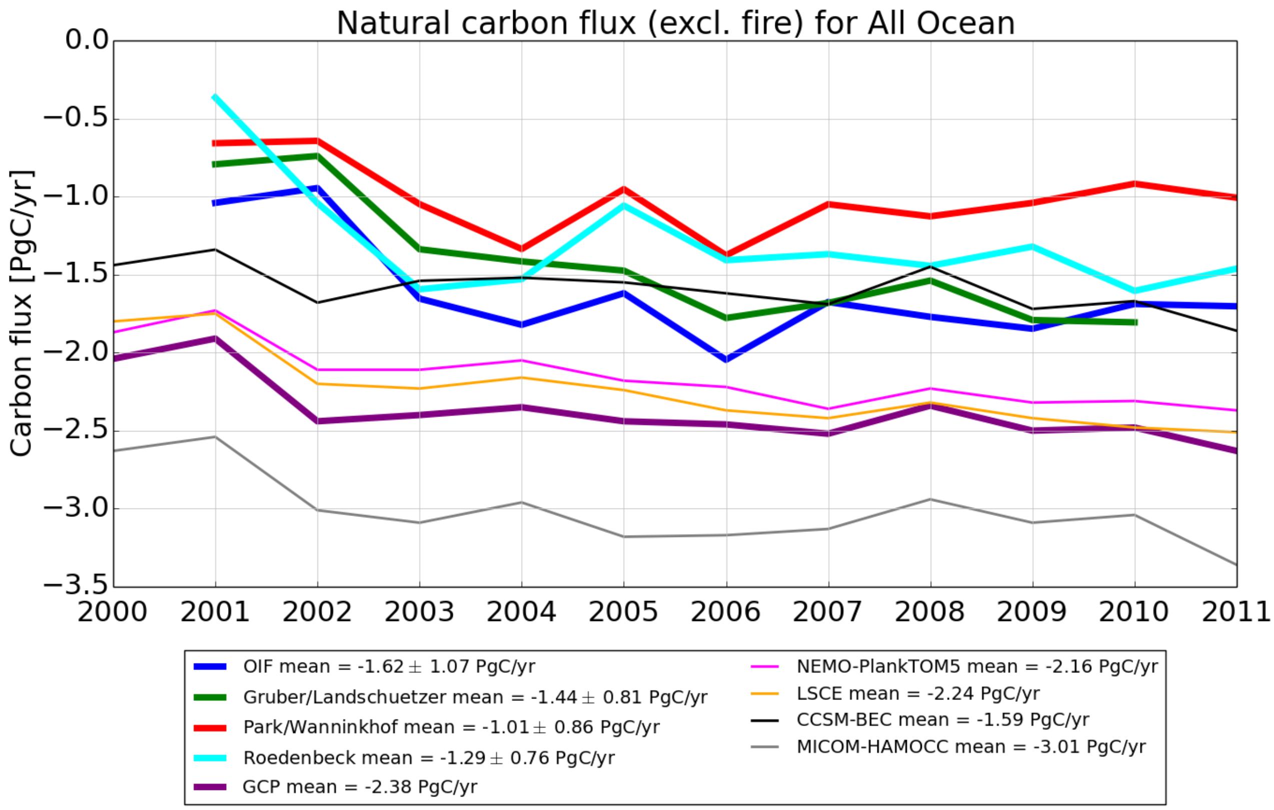

Figure 3: Optimized ocean fluxes from the 4 different inverse models using atmospheric observations in comparison to the Global Carbon Project estimates using forward models without data assimilation and the respective mean of these forward models (bold line GCP mean). Source: Van der Laan-Luijkx et al (GEOCARBON internal report).

In the deliverable report D9.2, figure 2.3.1, the results for the global CO2 flux from the PELAGOS model used at CMCC showed somewhat higher interannual variability, but an unrealistically strong ocean carbon sink. Results improved after a revision of the initial conditions and the inclusion of the ocean spin-up described in Sec. 2.1 above. In **Figure 4** we show the global ocean CO2 flux from the PELAGOS model from Experiment B in Table 1, for CTRL (blue line) and TSREAN (red line). The inclusion of the physics reanalysis leads to a value of the global ocean CO2 flux which agrees with results from other ocean models, see **Figure 3**. The flux from the REAN run, in which additional DIC and ALK data are included in the data assimilation, predicts the ocean to be a CO2 source after the year 1998. This negative result has not been shown, since further investigation is required.

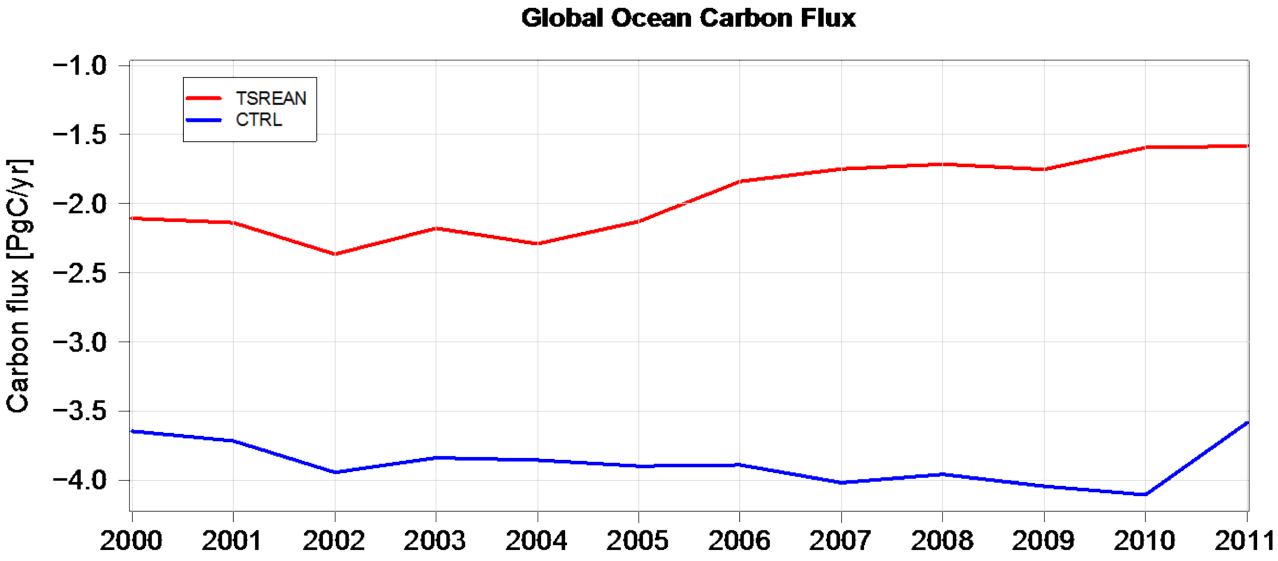

Figure 4: Oceanic CO2 fluxes from Experiment B in **Table 1**, obtained with the PELAGOS model used at CMCC. Lines are CTRL (blue) and TSREAN (red).

It may be premature to analyse the change in ocean carbon sink variability as long as the big difference between the atmospheric inversions and the ocean model simulations (with or without data assimilation) exists and cannot be explained satisfactorily. This offset exceeds the interannual variability by one order of magnitude. Further, among the different approaches there are significant agreements concerning the direction of change from one calendar year to the next. Potential candidates for explaining the strong difference in annual air-sea CO_2 fluxes among the different approaches are

The atmospheric inversions determine the total air-sea CO_2 flux including natural plus anthropogenically induced fluxes. Forward models usually include no preindustrial natural net flux between ocean and atmosphere. This is illustrated in **Figure 5**.

- The atmospheric observations are biased to specific regions with specific uptake characteristics.
- The ocean observations used for calibrating the forward models are induce a bias due to spatio-temporal heterogeneity.
- The 3-D ocean circulation allows vertical redistributions of carbon within the ocean that cannot be diagnosed by atmospheric inversions.

Of course, further other causes may be behind the substantial discrepancies between the current results. As completely independent air-sea CO_2 flux constraints do not exist, and one relies for global estimates on models and inverse approaches including assumptions, no rigorous decision for a grading of the different approaches concerning the strength and temporal evolution of marine CO_2 sink can be made as yet. This somehow difficult situation could be improved through an optimisation of the forward model's mean state with respect to physics and biogeochemistry and through a higher spatial model resolution resulting in stronger regional variability.

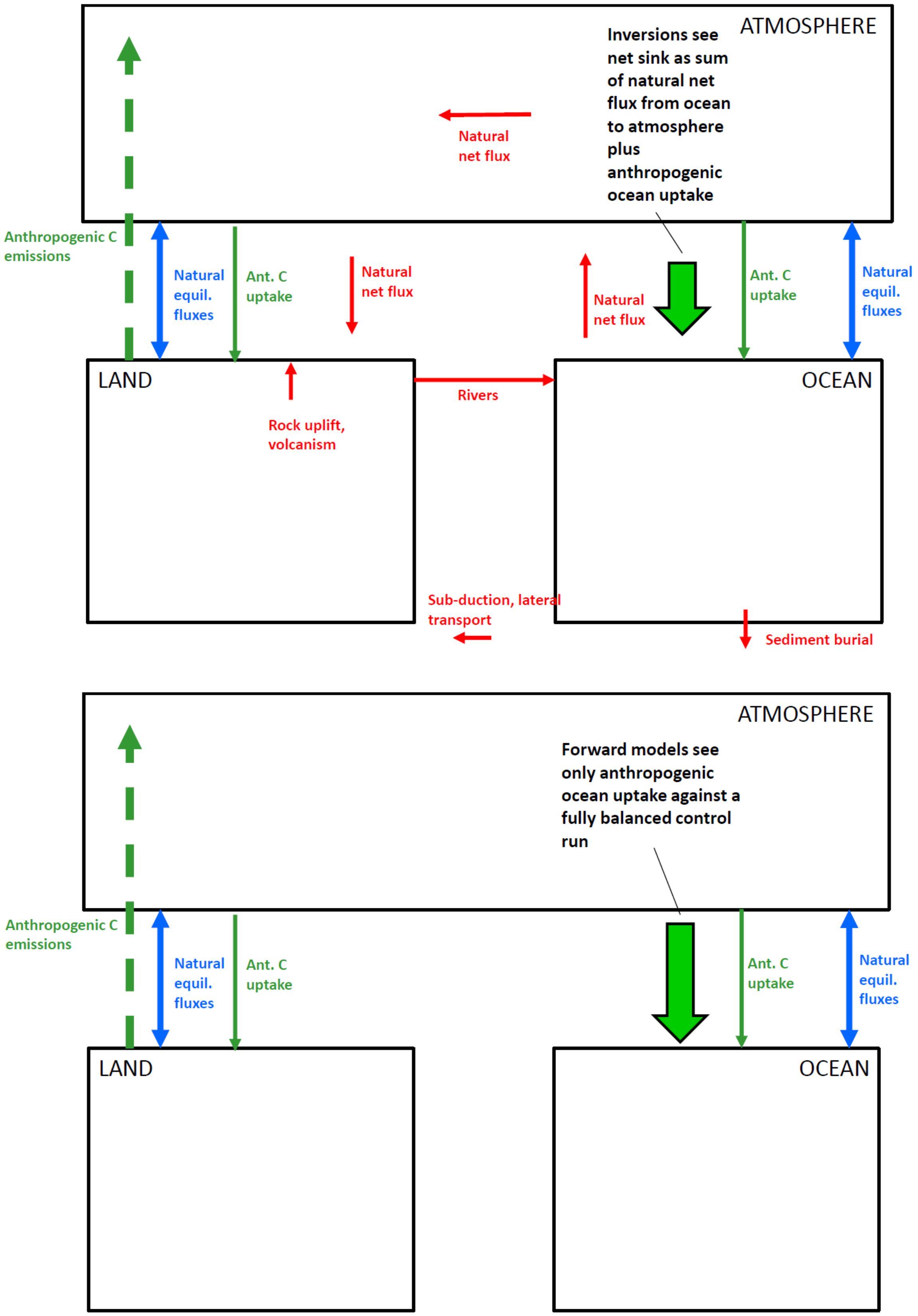

Figure 5: The ocean net sink for CO_2 as seen by atmospheric inversions form the "real" world situation (top) and as seen by forward models without land-ocean coupling (bottom).

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