Stiftung Alfred-Wegener-Institut
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# State estimation in support of an iron fertilization experiment in the Antarctic Polar Frontal Zone.

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## 1 Overview

The mutual availability of a high-resoltion data set and a suitable numerical ocean model makes a multivariate data-model analysis possible. In general, combining models and data with data assimilation or state estimation techniques is promising when both data and models separately exhibit skill. However, in oceanography more often than not, data and in particular subsurface data are sparse and the prediction skill of ocean models tends to be poor on long time scales. We present a state estimation experiment, in which we use high-resolution hydrographic, tracer and velocity data from the European Iron Fertilization EXperiment (EIFEX) to constrain a high-resolution coupled ecosystem-ocean circulation model of the experimental site in Atlantic sector of the Antarctic Polar Frontal Zone.

## 2 EIFEX: European Iron Fertilization EXperiment

EIFEX was aimed at testing the hypothesis that iron limits phytoplankton blooms in the Southern Ocean. For the open ocean experiment, a patch with a diameter of 15 km inside of a cyclonic, mesoscale eddy in the polar frontal zone was fertilized on February 12–13 and February 26–27, 2004 with dissolved iron. Subsequently the oceanic response was monitored. The eddy was identified with the help of in-situ measurements (CTD sensor and ship mounted ADCP) and satellite altimetry. It extended over 85 km by 120 km. with the center near 49°24’S 02°15’E in the South Atlantic During the course of the experiment both hydrographic and dynamic parameters and bio-geochemical quantities were measured at CTD stations inside and outside the fertilized patch and along the ship track. Airborne LIDAR-data were use to track the location of the bloom.

## 3 MITgcm and state estimation

The M.I.T. general circulation model (MITgcm Marshall et al., 1997) has been adapted for use with the Tangent linear and Adjoint Model Compiler (TAMC), and its successor TAF (Transformation of Algorithms in Fortran, Giering and Kaminski, 1998). Efficient (w.r.t. CPU/memory), exact (w.r.t. the model’s transient state) derivative code can be generated for up-to-date versions of the MITgcm and its newly developed packages in a wide range of configurations (Heimbach et al., 2002, 2005). Here, the MITgcm is configured to cover the experimental region of the EIFEX cruise of appoximately 150 km by 194 km with a mean horizontal grid spacing of approximately 3.6 km; vertical grid spacing increases from 10 m near the surface to 25 m at 500 m depth. The integration time spans the length of the experiment (39 days).

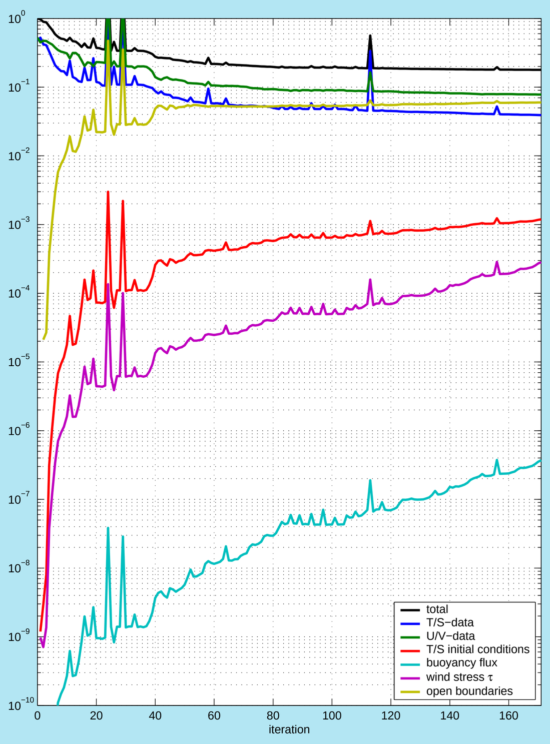


**Figure 1:** Evolution of different contributions to the objective function $J$ with iteration number of the BFGS-descend algorithm. Hydrographic data from CTD-stations and ship-mounted ADCP-current measurements are used to assimilate the model using the variational data assimilation technique (state estimation, “4D-VAR”). During the minimization of the objective function $J$ that describes the quadratic deviation of the model from data and also penalizes deviations from the first guess, initial conditions for temperature and salinity, open boundary conditions for temperature, salinity, and velocity, and surface fluxes of heat, fresh water, and momentum are adjusted to give the best fit to observations.

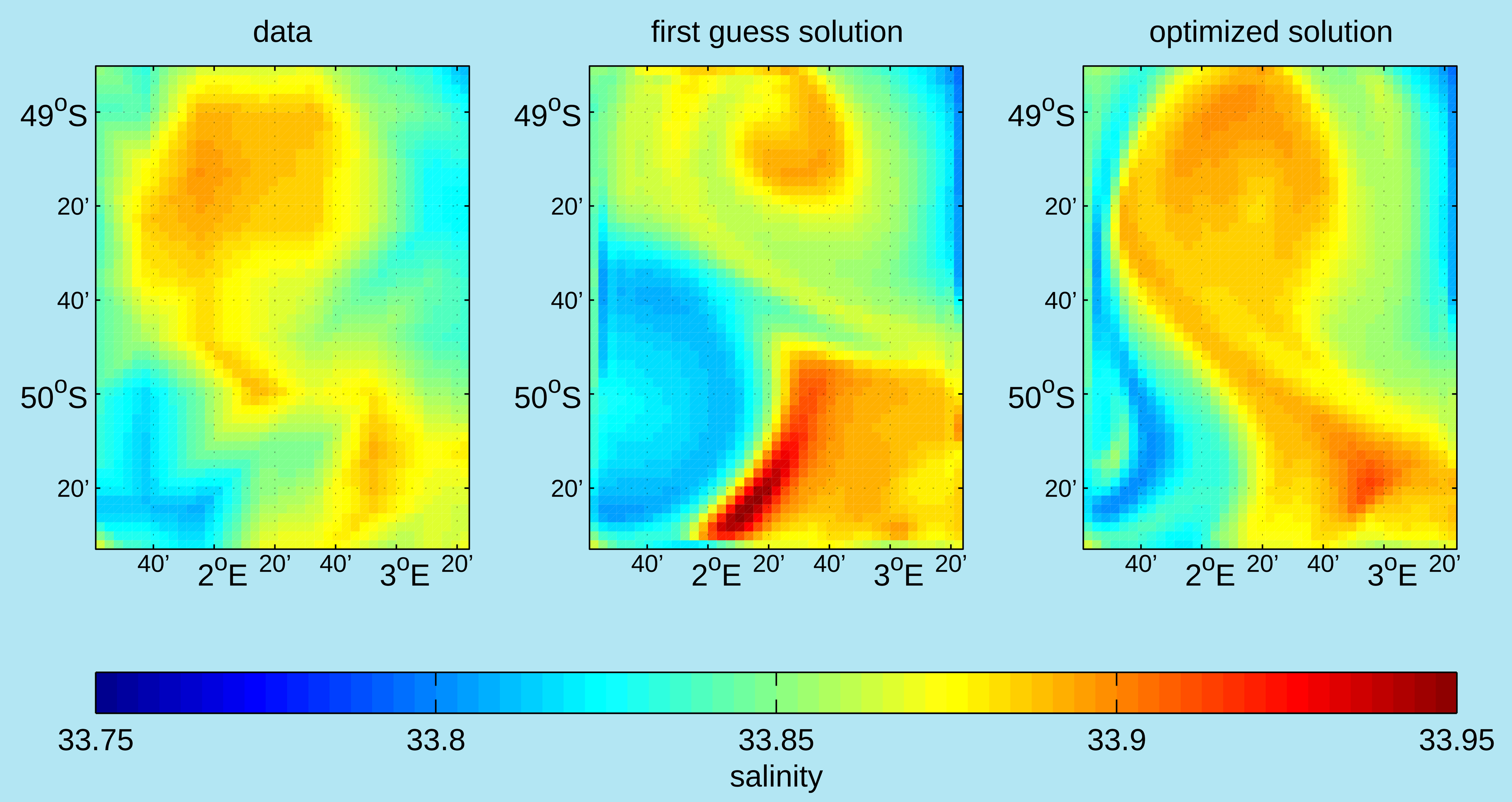


**Figure 2:** Comparison with in-situ data shows that data assimilation improves the position of the eddy by adjusting open boundary conditions, initial hydrography, and (to a lesser extend) surface flux boundary conditions. Left: surface salinity from hydrographic measurements, average over first 10 days of the experiment. Center: surface salinity of modeled eddy on day 5 without data assimilation; initial conditions and boundary conditions for this first guess are obtained by interpolating and extrapolating all available data; the amount of data is not sufficient to allow for time dependent boundary conditions, which appears to be the major problem for this solution. Right: surface salinity of modeled eddy on day 5 after full time-dependent state estimation; the eddy has moved southward and away from the boundary and its position is now in much better agreement with observations (Left).

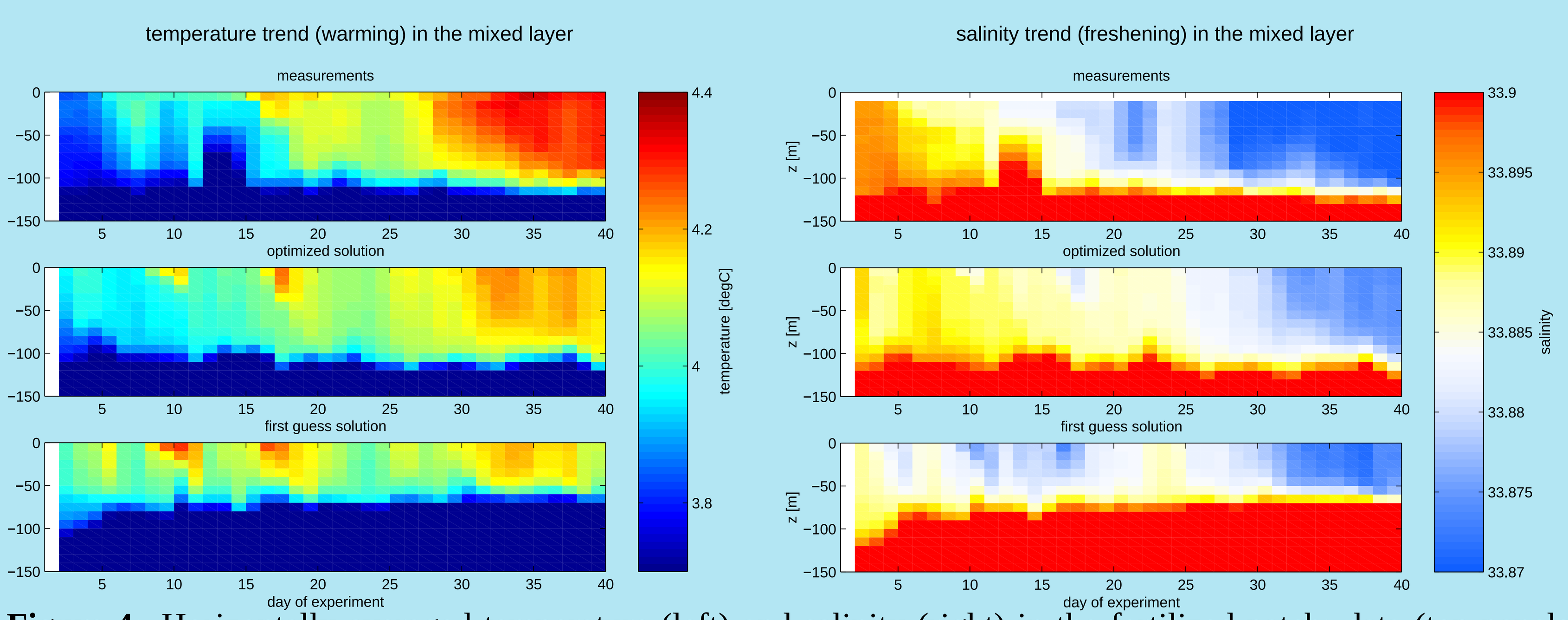


**Figure 4:** Horizontally averaged temperature (left) and salinity (right) in the fertilized patch; data (top panels), optimized model (middle panels), first guess model (bottom panels). The optimization improves the description of the mixed layer depth dramatically, so that the optimized solution describes the warming and freshening of the mixed layer more accurately than the first guess solution.

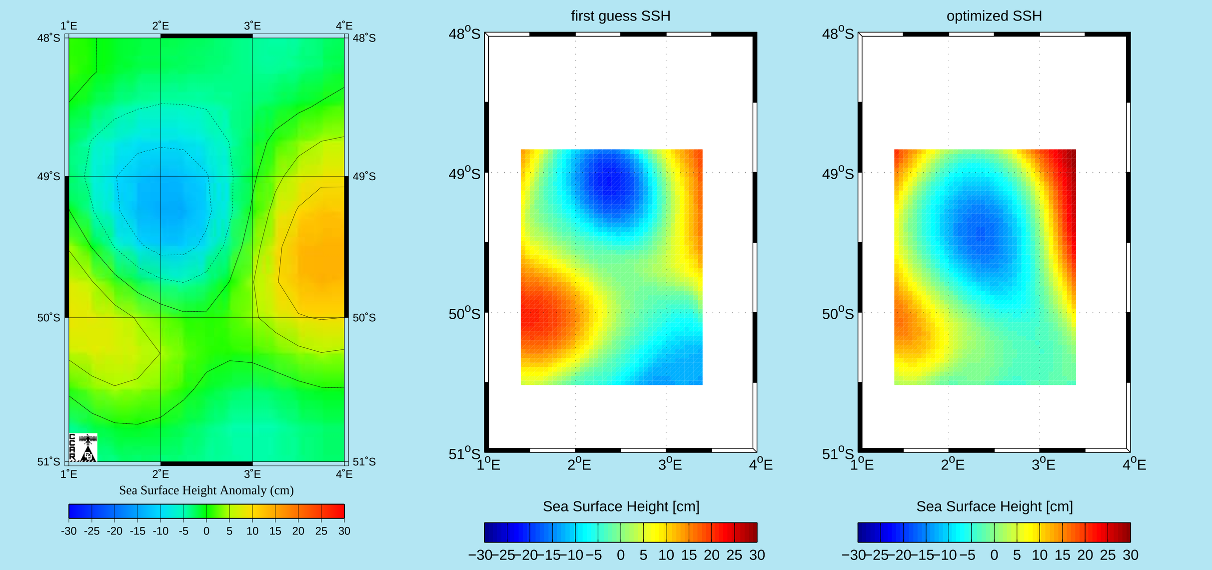


**Figure 3:** Left: sea surface height (SSH) anomaly from satellite altimetry on day 37 of the experiment (not used in the assimilation; source: `http://www-ccar.colorado.edu/~realtime/gsfc_global-real-time_ssh`). Center: SSH of modeled eddy on day 37 without data assimilation. Right: SSH of modeled eddy on day 37 after full time-dependent state estimation; the eddy extends further south than before, but the comparison of *absolute* SSH with height *anomalies* is ambiguous.

## 4 Ecosystem Model REcoM: Comparison to Observations

In our study we use a newly developed regulated ecosystem model (REcoM, Schartau et al., 2007) that is based on an approach of Geider et al. (1998). It explicitly decouples carbon and nitrogen fluxes and does not rely on a fixed Redfield ratio. For Southern Ocean applications, REcoM has been extended to account for diatom blooms, opal export, and iron explicitly (Hohn et al., 2007). Four additional state variables have been added: silicate, iron, and biogenic silicate compounds in phytoplankton and detritus. This model is coupled to the physical circulation. Initial conditions for the 16 state variables of REcoM are estimated from observations and 1D-sensitivity and tuning experiments (not shown).

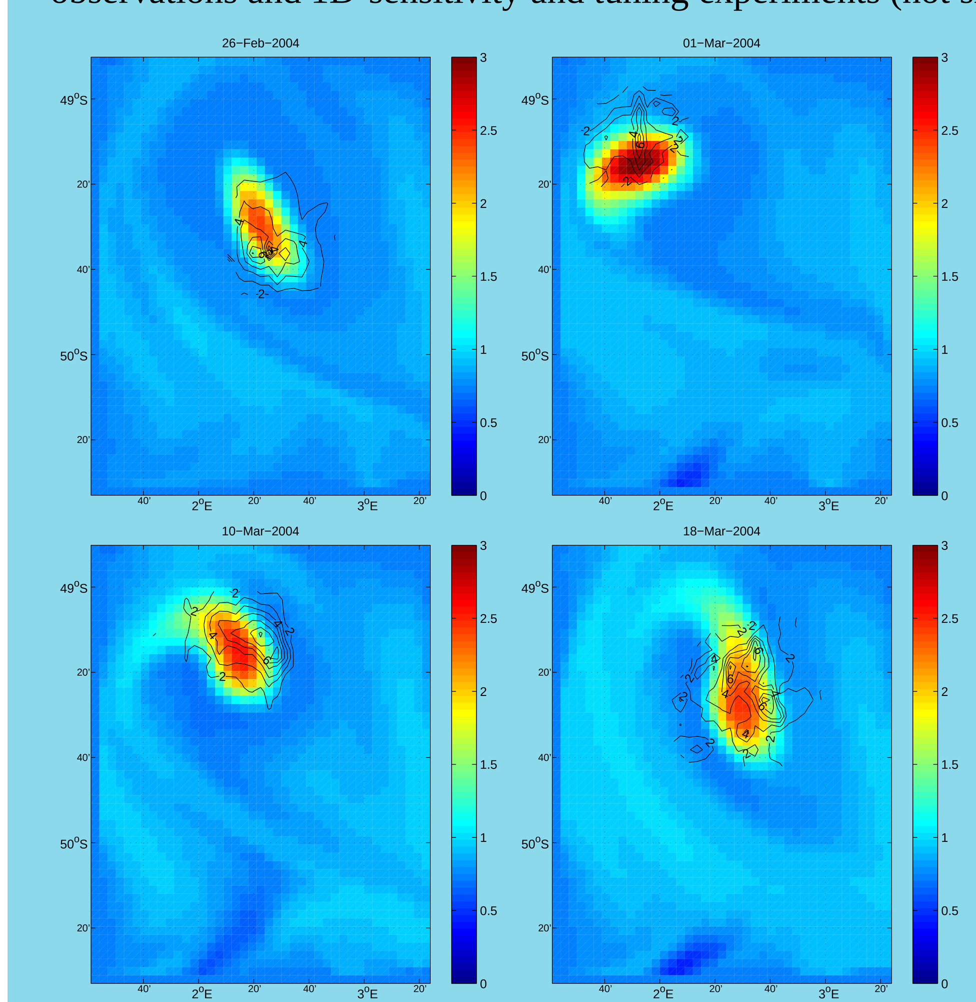


**Figure 5:** Model surface chlorophyll concentration (in $mg\,m^{-3}$) on selected days (15, 19, 28, and 36 days after fertilization). Overlaid are contours of normalized LIDAR-derived fluourescence giving an impression of the observed bloom location.

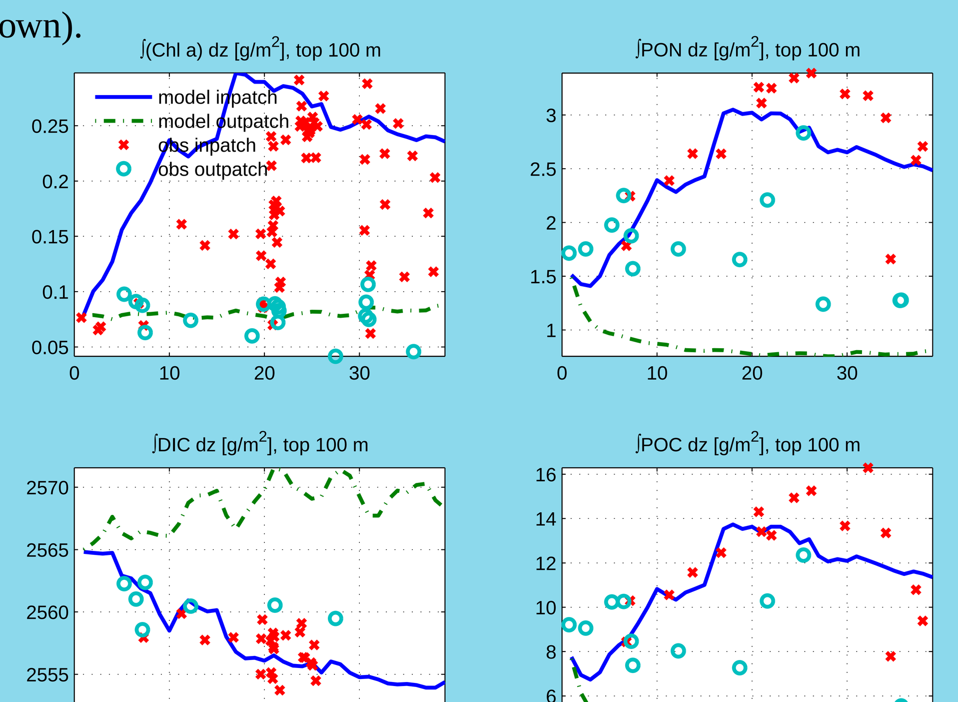


**Figure 6:** Integral of top 100 m of observed and modeled chlorophyll a ($gChl\,m^{-2}$) and POC ($gC\,m^{-2}$) concentrations in the fertilized patch.

Both particulate organic matter (POM) and the uptake of dissolved inorganic carbon (DIC) appear to be slightly underestimated during the peak of the observed bloom, consistent with the too early maximum of chlorophyll concentration in the model. Note that POM outside the patch drops immediately after the beginning of the intergration contrary to observations. This drop of approximately $4\,gC\,m^{-2}$ is a consequence of the constant sinking velocity imposed in REcoM. DIC outside the patch increases in contrast to observations.

## 5 Results: Nutrient Budgets and Flux Estimates from the Coupled Ecosytem Circulation Model

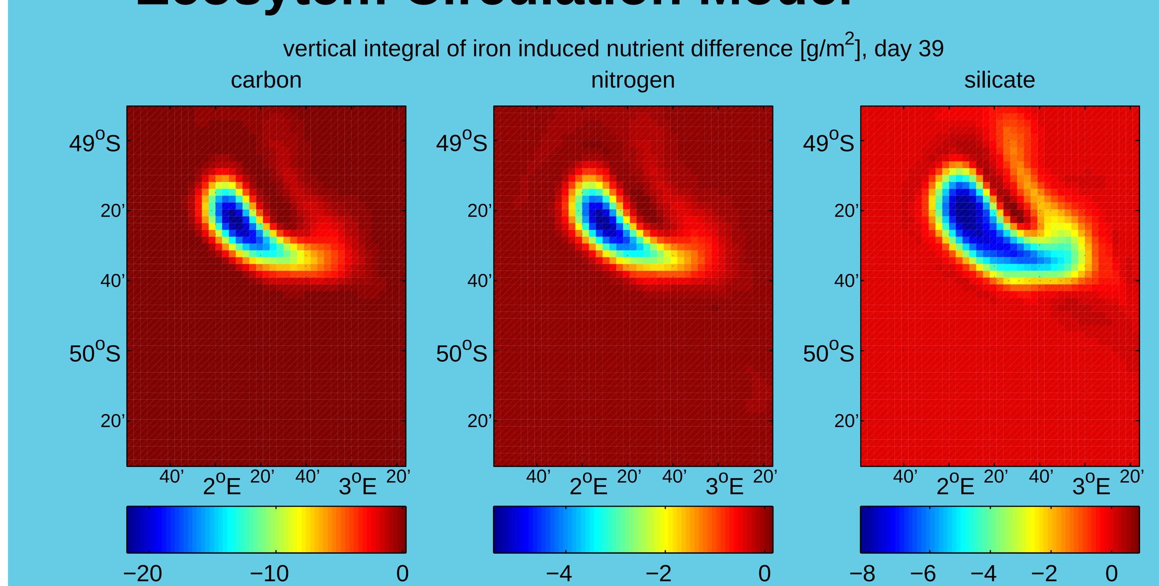


**Figure 7:** Estimated carbon, nitrogen, and silica consumption through biological activity induced by iron fertilization: difference (deficit) of nutrients at the end of the integration for experiments with and without iron fertilization. From carbon inventories in the run with iron fertiliztation, we esimate a total change of DIC of 10–15 $gC\,m^{-2}$ over 38 days (Fig. 6), which falls within the range of estimates by Smetacek et al. (2008) when surface gas exchange is excluded from the calculation. The DIC difference between runs with and without iron fertilization, integrated to 100 m depth, peaks at 16.8 $gC\,m^{-2}$. The value increases to 23.6 $gC\,m^{-2}$ if integrated to 500 m (bottom of the domain, see figure).

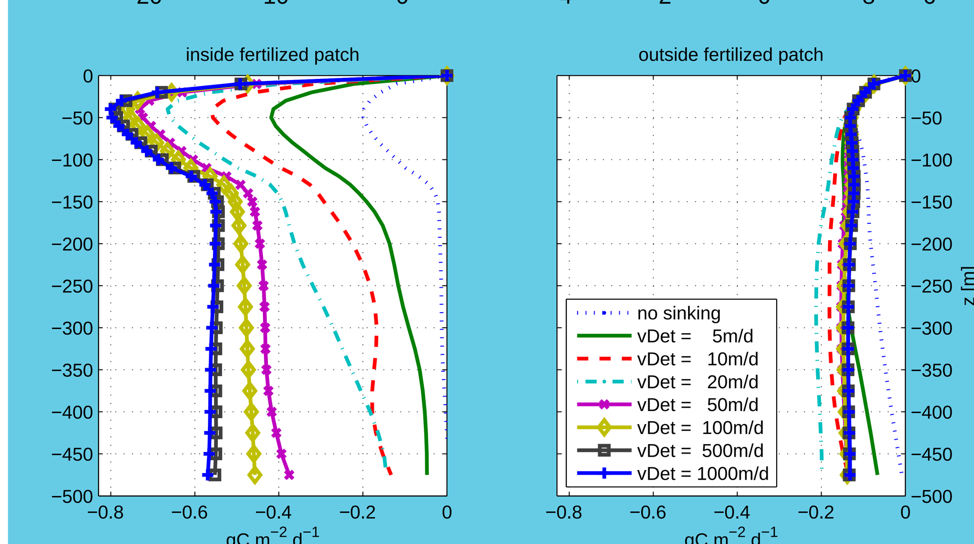


**Figure 8:** Vertical flux of particulate organic carbon (POC, in $mmol\,C\,m^{-2}\,s^{-1}$) averaged over the fertilized patch and the last 10 days of the experiment. Here we estimate the effect of the sinking velocity. Changing this constant parameter has a large effect for small values (below 100 m/d) but becomes less important for large values.

**Conclusions:** This study provided the rare opportunity to investigate the oceanic response to an iron fertilisation experiment over a period of about 38 days within a mesoscale eddy at the Southern Polar Front. In a first step we showed that the 3D global state estimate from hydrography and velocity data are in good agreement to the observations. The result form the ecosystem model REcoM are promising, because the modeled chlorophyll concentrations coincide with the LIDAR-derived fluorescence data and the derived nutrient budgets and flux estimates are on the same order as direct estimates from observations.

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