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(Synthesis)

BELCANTO II

ASSESSING THE SENSITIVITY OF THE SOUTHERN OCEAN'S BIOLOGICAL CARBON PUMP TO CLIMATE CHANGE

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The research described in the present report focused on the role of the Southern Ocean in global change. It was carried out by an interdisciplinary network of biologists, geochemists, and physical and ecological modellers (BELCANTO: BELgian research on Carbon uptake in the ANTarctic Ocean). The objective was to apply and develop geochemical proxies and numerical tools for assessing and understanding the present-day functioning of the CO_2 biological pump in the iron-limited Southern Ocean and predicting its evolution in response to scenarios of increasing atmospheric CO_2. The research methodology involved and combined existing and new field data (cruises shown in Figure 1), laboratory process-level studies and numerical work in order to improve our understanding of the mechanisms controlling the production of key bloom-forming phytoplankton groups of the Southern Ocean (diatoms and *Phaeocystis*), their sinking rate and biodegradation when exported in the mesopelagic zone (100-1000 m).

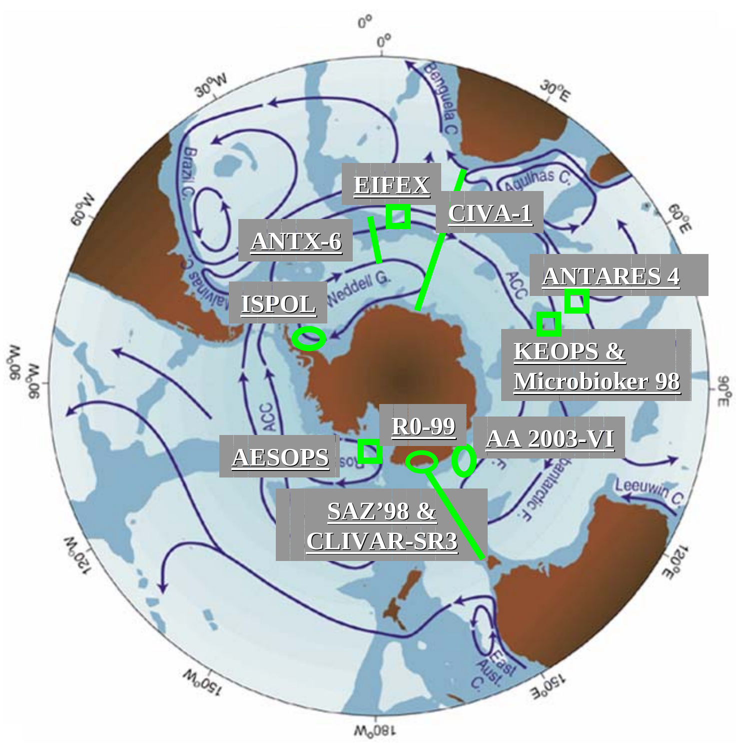

Figure 1: Southern Ocean expeditions to which BELCANTO scientists contributed the past decade.

Light and nutrient controls of phytoplankton growth, sinking rates and microbial degradation of phytoplankton detritus: Laboratory experiments under controlled conditions

Nowadays there is little doubt that iron availability plays a pivotal role in structuring the phytoplankton community of the Southern Ocean. Large (20-100 μm) diatom cells have indeed higher iron requirements than nano-sized (<20μm) cells (Sunda and Huntsman, 1998; de Baar et al., 2005). Iron and light are currently reported as important co-limiting factors of phytoplankton growth (Armstrong, 1999; Boyd et al., 2000). In order to improve current knowledge on iron and light control of Antarctic phytoplankton growth and sinking rate, we ran experiments on cultures of *Phaeocystis antarctica* (Haptophyceae) and *Thalassiosira gravida* (diatoms), which are two widespread species of the Southern Ocean.

Experiments were conducted using trace metal ultra-clean methods on cultures set up in natural low iron (<1nM Fe) and –enriched (+2nM Fe) Antarctic seawater. The effect of Fe addition on the morphological forms, Fe assimilation, the photosynthetic parameters, growth and biochemical composition of *P. antarctica* and *Thalassiosira gravida* was assessed. We also estimated potential sedimentation rates under limiting and non-limiting conditions. Results showed an effect of Fe addition on the morphological form, enhancing the presence of the colonial form compared to the free-living cells for *Phaeocystis* and increasing the appearance of long chains of diatoms vs. free living cells. Maximum photosynthesis increased under Fe enriched conditions. In contrast, there was no effect of Fe enrichment on the saturating light intensity. The production of small metabolites increased under Fe replete conditions. Due to changes in the morphological form, Fe:C protein ratios were approximately three times higher under Fe limiting conditions for *Phaeocystis*. In contrast, Fe:C protein ratios were higher under Fe enriched conditions in the case of *Thalassiosira gravida*. Higher sedimentation rates were measured under the Fe enriched condition.

Heterotrophic bacteria may influence the efficiency of carbon export through the remineralisation of particulate organic matter (POM) associated with aggregates but also of dissolved organic matter (DOM) remineralisation (Ducklow et al., 2001). Iron, an essential nutrient which limits primary productivity in the HNLC regions, has been put forward as one of the factors limiting the bacterial growth in the Southern Ocean (Tortell et al., 1996). Nevertheless, the extent to which Fe regulates bacterial dynamics in the HNLC area remains unresolved. The response of heterotrophic bacteria to iron supply might be twofold: either directly to the Fe supply and/or indirectly through the supply of higher concentration and/or due to the better quality of organic substrates derived from iron-enhanced phytoplankton production (Pakulski et al., 1996; Church et al., 2000; Kirchman et al., 2000). In the present study, the bacterial community response to the iron supply was investigated through re-growth experiments monitoring the bacterial response to organic substrates derived from *Phaeocystis antarctica* and *Thalassiosira gravida* cultures grown under iron-enriched and iron-limiting conditions. Our results suggest that the bacterial activities (e.g. ectoenzymatic activities, growth rates and growth efficiency) are not directly enhanced by iron addition, but rather by the improved quality of the phytoplankton-derived organic matter from cultures enriched with Fe. Consequently, the bacterial remineralisation of organic carbon is more efficient in non - Fe limited areas.

Air-sea CO_2 fluxes

Based on measurements of underway partial pressure of CO_2 (pCO_2) we budgeted spring and summer air-sea CO_2 fluxes using Sea Surface Temperature (SST), chlorophyll-a concentration (Chl-a) and wind speed inferred from remote sensing data. We focused on the Indian sector (20°E-150°E; 30°S-60°S) from October 1997 to December 1999. CO_2 fluxes were partitioned according to the main oceanographic provinces of the Southern Ocean, namely the subtropical zone (STZ), both north and south subantarctic zone (denoted as NSAZ and SSAZ respectively), polar frontal zone (PFZ) and polar open oceanic zone (POOZ), using the positions of fronts derived from SST distributions (Kostianoy et al., 2003; Kostianoy et al., 2004). The CO_2 sink in the 35-50°S zonal band is centred on the SSAZ and the overall sink strength for this latitudinal band of the Indian sector ranges from -0.039 to -0.110 PgC in spring and from -0.032 to -0.093 PgC in summer. A further collaborative effort was carried out applying a similar approach to the western Pacific sector of the Southern Ocean (Rangama et al., 2005). Integrating CO_2 fluxes over the year shows that the studied area acts as a sink for atmospheric CO_2 of -0.08 PgC yr^{-1}. Both studies exhibit lower estimates than previous ΔpCO_2 - based studies (Metzl et al., 1995, Metzl et al., 1999; Takahashi et al., 2002), but corroborate the conclusions of inverse models indicating that ΔpCO_2 - based studies probably overestimate CO_2 fluxes in the Southern Ocean (Gloor et al., 2003; Gurney et al., 2004; Jacobson et al., 2005).

However, the role of sea ice cover in CO_2 budgets of the Southern Ocean has been neglected, since it was assumed as an impermeable and inert cover that prohibited air-sea fluxes of gases. However, direct measurements of pCO_2 within sea ice and related air-sea ice CO_2 fluxes point out that CO_2 fluxes over the Antarctic sea ice cover may represent a significant additional sink. Indeed relatively warm sea ice is permeable to gases and liquids, and there is growing evidence for gas exchange between sea ice and the atmosphere. We report the first direct measurements of pCO_2 within sea ice and related CO_2 fluxes at the air-sea ice interface. pCO_2 dynamics within sea ice are mostly independent of pCO_2 in the underlying layer. Internal spring and summer sea ice specific processes (dilution with ice crystals, dissolution of carbonate minerals), together with primary production, drive drastic decreases of pCO_2 and lead to marked undersaturation of CO_2 with respect to the atmosphere. Despite its thinness the Antarctic sea ice edge thus appears to sustain a significant uptake of atmospheric CO_2. We propose a first tentative and conservative estimate of air-ice CO_2 fluxes over the Antarctic sea ice edge as inferred from remote sensing data. In spring and summer, the sea ice edge acts as a sink of atmospheric CO_2 ranging from -0.015 to -0.024 PgC which represents 6% to 9% of the annual uptake of the Southern Ocean (-0.26 PgC yr^{-1}). However, we surmise that the present evaluation of the sea ice edge CO_2 sink is an underestimate since it does not account for the uptake of CO_2 by biologically active sea ice surface communities. This additional CO_2 sink should be taken into account when budgeting air-sea CO_2 fluxes in the Southern Ocean.

Assessment of Si-nutrient source and utilisation via a new proxy: Si isotopic composition

We analyzed $\delta^{29}Si$ of dissolved silicate for whole water column profiles across the Southern Ocean (spring 2001, CLIVAR-SR3 cruise along 1545°E line) between the Seasonal Ice Zone (SIZ) and the Subantarctic Zone (SAZ). These results include the first isotopic compositions measured for Si-depleted seawaters (Cardinal et al., 2005a). At all sites the surface mixed layer showed enrichment in heavy Si isotopes compared to underlying waters, in accordance with preferential uptake of the light isotope by diatoms. As silicate levels decrease northwards from the SIZ across the Polar Front Zone (PFZ) to the SAZ, surface and mesopelagic δ^{29}Si signatures generally become progressively heavier. However, the most Si-depleted SAZ waters do not exhibit δ^{29}Si values exceeding those in the PFZ. This unexpected situation appears to derive from variations in the vertical and horizontal supply of silicate to surface waters, and by applying a steady-state open system model, we estimated a fractionation factor $^{29}\varepsilon$ between diatoms and seawater of -0.45 ± 0.17‰, independently of zones and phytoplankton community composition. Latitudinal changes in mesopelagic δ^{29}Si values, complexity in surface silicate - δ^{29}Si correlations, and differences with previous studies underline the need for caution in the use of δ^{29}Si in paleoceanographic studies until systematic efforts have been undertaken to better understand modern variations.

We also measured diatom silicon isotopic signatures during the same CLIVAR SR3 spring cruise. Total (>0.45um), medium-sized (20<<70um), and large diatoms (>70um) were sampled in the upper 150m. The isotopic composition of diatoms is generally homogeneous in the mixed layer and does not exhibit isotopic fractionation linked to size or depth of occurrence. Diatom δ^{29}Si is systematically lower than silicate δ^{29}Si, reflecting preferential uptake of light isotopes by diatoms. Both, for diatoms and silicate we observe a trend of isotopic signatures getting lighter southward, but for diatoms the gradient is much steeper with δ^{29}Si values reaching as low as -0.26‰ at the southernmost SIZ station and contrasting strongly with the +0.65‰ value for diatoms in the PFZ. This suggests that diatoms and silicate in the mixed layer are subject to different time scales depending on zonally varying physical and ecological characteristics.

Carbon export and controls by Fe and ammonium

New production represents the fraction of primary production potentially exportable from the euphotic zone. During CLIVAR-SR3 in spring 2001, the Antarctic Zone South (AZ-S) and the Seasonal Ice Zone (SIZ) constituted the region of highest new production (up to 240 mg C m^{-2} d^{-1}) while new production in the SubAntarctic Zone

(SAZ), the Polar Front Zone (PFZ) and the Inter Polar Front Zone (IPFZ), values reached only about 70 mgC m^{-2} d^{-1}, with SAZ values slightly exceeding those for PFZ-IPZ. The AZ-S and SIZ had highest *f*-ratios, reaching up to 0.61. Lowest *f*-ratios were observed in the SAZ (0.38) and intermediate values (0.56) in the PFZ. The latitudinal trend of new production during spring 2001 along 145°E is similar to the one for ^{234}Th flux obtained for the same cruise.

Deficit of ^{234}Th activity (relative to its parent ^{238}U) in the upper mixed layer is indicative of particle export. Knowledge of POC/^{234}Th ratios of settling particles gives access to the POC export flux. During spring 2001 (CLIVAR-SR3) ^{234}Th fluxes along 145°E were low in the north (ca. 630 dpm m^{-2} d^{-1}), minimal in the Polar and Inter Polar Front Zones (ca. 300 dpm m^{-2} d^{-1}) and high in the south (ca. 3000 dpm m^{-2} d^{-1}). ^{234}Th export fluxes were converted into particulate organic carbon (POC) flux by multiplying with the POC/^{234}Th ratio of large particles (55-210µm), assumed to represent the sinking particles. During the CLIVAR-SR3 cruise export production ranged from 20 mgC m^{-2} d^{-1} in the PFZ to 670 mgC m^{-2} d^{-1} in the SIZ at 64°S. Our results indicate low particle export in the SAZ and SAF, very low particle export in the PFZ and IPFZ and high export in the AZ-S and SIZ during spring 2001. This latitudinal trend is in quite good agreement with new production data for the same cruise. The very low export production and new production in the PFZ and IPFZ contrast with the widely accepted idea that the Polar Front enhances primary and export production. This could be specific to the Australian sector because of local hydrodynamic conditions associated with a double front structure.

Iron and ammonium concentrations may strongly affect the relative importance of exportable production vs. total production (i.e. the *f*-ratio). In addition to their individual effects, the combined effect of ammonium and iron on *f*-ratio was investigated during spring 2001 (CLIVAR-SR3, 145°E). In the HNLC areas of the SAZ, PFZ and AZ-S *f*-ratio is lowered by ammonium addition and enhanced by iron addition. It was observed that enhancement of the *f*-ratio due to Fe addition depends on the ambient ammonium concentration and it thus appears that the combined effect of ammonium and iron is not simply cumulative. Our results imply that there is no simple relationship between export production and iron availability. Ammonium appears to counter the effects of iron addition on export production, particularly for HNLC areas such as the Southern Ocean.

We also investigated the effect of large scale in-situ iron amendment on carbon export. The EIFEX iron fertilisation experiment (January – February 2004) took place in a meso-scale eddy pinched off from the meandering Polar Front in the Atlantic sector. The experiment ran until the decrease of the export flux in contrast to other iron experiments in the Southern Ocean which were interrupted before significant export occurred. The eddy was fertilized with Fe and monitored for 36 days afterwards. A phytoplankton bloom dominated by diatoms was induced with chlorophyll contents reaching close to 3 µg l^{-1} three weeks after the iron infusion.
The ^{234}Th export fluxes at 100 m first decreased to near zero within the first two weeks after the iron infusion. Subsequently ^{234}Th fluxes increased, reaching values as high as 8000 dpm m^{-2} d^{-1} one month after the Fe infusion. Such a ^{234}Th flux is the highest ever recorded and suggests that the bloom broke up rather fast and sunk massively. During the last four days of the experiment the ^{234}Th flux decreased again to 1400 dpm m^{-2} d^{-1}. When integrated over the full period of export (i.e. days 15 to 36), the sinking of the Fe-induced bloom exported 44700 ± 8800 dpm m^{-2} of ^{234}Th. The evolution of ^{234}Th export versus time during EIFEX was strikingly similar to the one of mesopelagic Ba_{xs} content, a proxy for mesopelagic mineralisation of organic carbon.

*Mineralisation of exported organic car*bon

We assessed mineralization of exported organic carbon using the barium-barite proxy. Excess, non-lithogenic particulate Ba (Ba_{xs} , mainly consisting of barite) is associated with phytoplankton derived particles. In the twilight zone, a mesopelagic Ba_{xs} maximum is a recurrent feature which develops over the season and reflects the influx and mineralization of plankton detritus sinking from the mixed layer. During the summer (SAZ'98) and spring (CLIVAR-SR3) cruises along WOCE SR3 line (145°E) we observed significant zonal differences in mesopelagic Ba_{xs} contents. Compared to the SubAntarctic Zone (SAZ) mesopelagic Ba_{xs} contents during spring 2001 were larger and started to increase at shallower depths south of the Polar Front Zone (PFZ) and the Antarctic Zone (AZ), where diatoms were the dominant component of the phytoplankton community. During summer 1998, when mesopelagic Ba_{xs} accumulations were larger, a smilar latitudinal trend was observed (Cardinal et al., 2001). In contrast, the deep ocean flux of Ba_{xs} sampled by moored sediment traps was larger in the nano-phytoplankton dominated SAZ, than in the diatom dominated PFZ, as was observed also for deep particulate organic carbon fluxes. Overall, the results indicate relatively high particulate carbon export and absence of strong mesopelagic mineralisation (7.5–36% of export production) in the SAZ, but relatively low export and strong mesopelagic mineralisation further south in PFZ to SIZ (20-97% of export production). Mesopelagic carbon remineralisation was higher during summer compared to spring. Our findings are supported by results for the ^{234}Th and N-uptake proxies obtained for the same cruise.

In Figure 2 we reproduce our estimates for the different carbon fluxes that are part of the biological carbon pump, as obtained experimentally and via modelling.

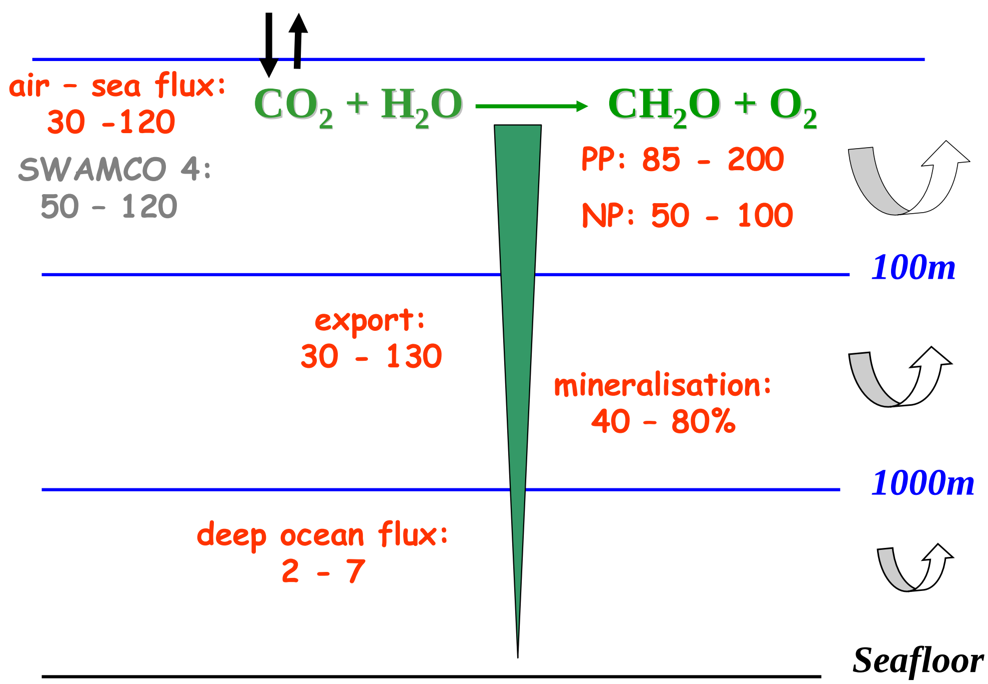

Figure 2: Synthesis of spring - summer carbon fluxes (mgC m^{-2} d^{-1}) driven by the biological pump (air-sea exchange; photosynthesis; particle export; mineralization; deep ocean particle flux); area between 35°- 54°S (SAZ and PFZ; Indian, Australian

sector); PP = Primary Production, NP = New Production; SWAMCO-4 = Modelled air-sea flux.

Simulating ice and ocean variations

The model *ORCA2-LIM* was used to study the ice-ocean system in the Southern Ocean. It results from the coupling of the Louvain-la-Neuve sea ice model (LIM) (Fichefet and Morales Maqueda, 1997) with the hydrostatic, primitive equation ocean model OPA (Océan PArallélisé) (Madec et al., 1999). In the standard configuration, the model is run on a global grid with 2° nominal resolution and a mesh refinement in high latitudes and near the equator. As a consequence, the meridional resolution increases to 0.5° close to the Antarctic continent, corresponding to a horizontal grid width of ~50 km. Vertical discretization uses 30 z-levels, with 10 levels in the top 100 m. Daily 2-m air temperatures and 10-m winds from the NCEP/NCAR reanalysis project for the period 1948–1999 (Kalnay et al., 1996), and monthly climatologies of surface relative humidity, cloud fraction, and precipitation rate are utilized to drive the model. The coupled model provides reasonable results as discussed in Timmermann et al. (2005). In particular, the simulated sea ice thickness has been compared with thicknesses from the Antarctic Sea Ice Processes and Climate (ASPeCT) database in Timmermann et al. (2004).

We have also used the ORCA-LIM model to analyze the influence of the Southern Annular Mode (SAM) on the ice-ocean system. We have shown that the surface transport anomalies associated with a positive phase of SAM are directed towards the northwest at high latitudes (south of 45°S) inducing an upwelling that features a maximum around 65°S and a downwelling at about 45°S (Lefebvre et al., 2004). Furthermore, the enhanced winds during years with positive SAM index imply a stronger stirring of the water column and a deeper mixed layer during all seasons. The latter and the modification in the intensity of the upwelling, which could both have an impact on the availability of nutrients in the upper ocean, might well affect the biological production in the Southern Ocean. The impact of the SAM on the ocean surface temperature and on the ice concentration varies strongly for the different regions of the Southern Ocean. Because of the southerly winds, the surface temperature and ice concentration are lower cover in the Ross and Amundsen Seas during years with positive SAM index while, at the same time, the SST increases and the ice-covered area decreases in the Weddell Sea because of northerly winds. Integrated over the Southern Ocean, these regional differences tend to cancel out, so that signals in the zonally integrated SST and ice concentration are very small (Lefebvre et al., 2005).

In addition, the results of various climate models have been analysed in order to understand the mechanisms responsible for the response of the Southern Ocean to an external forcing. First of all, an ensemble of simulations has been performed with the climate model ECBILT-CLIO driven by natural and anthropogenic forcings covering the period 1000-2000 AD. Over the last 250 years, the annual mean ice area has decreased by about $1x10^6$ m^2 in those simulations (Goosse et al., 2004; Goosse and Renssen, 2005). A comparison with experiments driven by only natural forcings suggests that this reduction is due to both natural and anthropogenic forcing, the latter playing a larger role than natural forcing over the last 150 years. Despite this contribution from anthropogenic forcing, the simulated ice area at the end of the 20^{th} Century is similar to the one simulated during the 14^{th} Century because of the slow response of the Southern ocean to radiative forcing.

Secondly, outputs from simulations performed with current atmosphere-ocean general circulation models for the Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC AR4) have been used to investigate the evolution of sea ice over the 20th and 21st centuries (Arzel et al., 2005). Overall, there is a large uncertainty in simulating the present-day sea ice coverage and thickness and in predicting sea ice changes in both hemispheres. Over the period 1981-2000, we find that the multimodel average sea ice extent agrees reasonably well with observations in the Northern Hemisphere despite the wide range of model responses but larger uncertainties appear in the Southern Hemisphere. The climate change projections over the 21^{st} century reveal that the amplitude of the seasonal cycle of sea ice extent increases in a warming climate and the annual mean sea ice extent decreases at similar rates in both hemispheres.

Development and performances of SWAMCO-4-ORCA-LIM

The idealized SWAMCO-4 model of the marine planktonic system calculating C, N, P, Si, Fe cycling within the upper ocean, the export production and the exchange of CO_2 between the ocean and atmosphere has been developed and validated during BELCANTO-2. The model, constrained by physical, chemical and biological (grazing, lysis) controls, explicitly details the dynamics of four relevant phytoplankton functional groups with respect to C, N, P, Si, Fe cycling and climate change. Those are diatoms, pico/nano phytoplankton, coccolithophorids, and *Phaeocystis spp*. whose growth regulation by light, temperature and nutrients has been obtained based on a comprehensive analysis of literature reviews on these taxonomic groups. The performance of SWAMCO-4 has been first evaluated in a 1D physical frame throughout its cross application in Southern Ocean provinces with contrasted key species dominance, export production, CO_2 air-sea fluxes and where biogeochemical time-series data are available for model initialisation and comparison of results. These are: (i) the ice-free Southern Ocean Time Series station KERFIX (50°40S, 68°E) for the period 1993-1994 (diatom-dominated) and (ii) the sea-ice associated Ross Sea domain (Station S; 76°S, 180°W) of the Antarctic Environment and Southern Ocean Process Study AESOPS in 1996-1997 (*Phaeocystis*-dominated). The ocean response to increased atmospheric CO_2 was then explored by running SWAMCO-4 at the two locations over the last decade. Results show that at all tested latitudes the prescribed increase of atmospheric CO_2 enhances the carbon uptake by the ocean. However the amplitude of the predicted atmospheric CO_2 sinks displays large regional and inter-annual variations due to the actual meteorological forcing that drives the local hydrodynamics. This is particularly true in the marginal ice zone of the Ross Sea (AESOPS) where the magnitude of the predicted annual CO_2 sink is positively related to the length of the surface ocean ice-cover period which determines the iron surface concentration at the time of ice melting.

As a first step towards the assessment of the Southern Ocean uptake of atmospheric CO_2, the SWAMCO-4 model was coupled to the 3D ice-ocean ORCA-LIM model implemented in the domain south of latitude 30° with a grid of ~ 50km. Prior to its coupling with ORCA-LIM, the trophic resolution of SWAMCO-4 was simplified based on numerical experimentations aiming at obtaining identical ecosystem behaviour with however a reduced number of state variables.

ORCA2-LIM-SWAMCO4 simulations were run from September 1999 to August 2000, using daily atmospheric forcing. Initial conditions were those corresponding to the KERFIX station and no additional source (from below and/or from the top) of Fe was considered. The simulated temporal shift of algal blooms towards south latitudes indicates that the model well describes the dual effect of available light (combination of latitudinal and ice coverage effects) and Fe limitation in controlling primary production. Further work will seek to improve the description of algal blooms associated with the ice retreat through better constrains of iron sources in the Southern Ocean and mesozooplankton grazing.