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Climatic changes and the cycle of carbon

210 participants, 19 nations, 5 continents

Synthesis

Question 1 : What role does the Southern Ocean play in the contemporary global carbon cycle ?

A bout 500,000 pairs of air and sea pCO_2 measurements have been made over the world ocean. A method of interpolation has been presented to compute the climatological distribution of the sea-air pCO_2 difference for each month during a reference year 1995. The results show the Southern Ocean acts as a significant net sink for atmospheric CO_2. This sink is centered near 50°S (between 35 and 60°S), it is more pronounced in the Atlantic and in the Indian sector and less in the eastern Pacific sector. It is attributed to the juxtaposition of the cooling effect on warm subtropical waters and the biological utilization effect on nutrient-rich subantarctic waters. South of 50°S the present best estimate for this sink is 0.6 GT C yr^{-1}, i.e. about 30% of the global ocean CO_2 sink. A model study shows the penetration of anthropogenic CO_2 is very active south of 50°S but its storage is low because anthropogenic carbon is rapidly transported northward isopycnally into the SubTropical Convergence. The modelled interannual variability of the net atmospheric CO_2 sink, due to the Antarctic Circumpolar Wave (linked to ENSO), is estimated at $\pm$ 0.2 GT C yr^{-1}.

Question 2 : What controls the magnitude and variability of primary production and export production ?

Access to satellite data has allowed more realistic estimates of the primary productivity of the different subsystems of the Southern Ocean. The best estimates for average primary productivity range between 60 and 100 gC m^{-2} yr^{-1}, i.e. 3 to 5 times higher than those of the beginning of the 1990s, deduced from extrapolated ^{14}C measurements.

Evidences of limitation of the primary productivity by iron and or by silicic acid are now clearly demonstrated. As shown by the iron fertilization experiment *SOIREE* the biological pump of CO_2 reacts rapidly to dissolved iron addition in surface water, although the export of biogenic material out of the photic layer seems to be delayed. This experiment showed the small (prymnesiophytes) phytoplankton drove the S cycle, while the large diatoms were responsible for most of the C fixation - and hence drove the C cycle. As the timing and magnitude of the *SOIREE* bloom evolution are similar to other naturally-occuring blooms in the open Southern Ocean, we may be able to use *SOIREE* as a physiological/biogeochemical model of such blooms. All in all however there remains substantial uncertainty about the processes and factors that regulate primary productivity, and particularly its variability, in the Southern Ocean. The Southern Ocean-Synthesis Group intends to further address this question during the ongoing Synthesis of the Southern Ocean.

Well documented dissolved nutrient distributions for the world ocean have been used to derive the rate constants of biogeochemical processes responsible for the observed fields using inverse modelling. The total annual export of POC necessary for the reproduction of the nutrient fields of the world ocean is 11 GTC yr^{-1}, about 1/3 being localized south of 30°S. This inverse modelling approach shows the export production of biogenic matter out of the surface layer is very efficient for the Southern Ocean. This is not in agreement with satellite derived estimates. If we are to give more realistic estimates for the export and primary production of the Southern Ocean these two approaches have to be reconciled. The conversion of algorithms is especially questioned, in areas like the Southern Ocean where subsurface chlorophyll maxima are not detectable by satellites.

There is a big gap between studies which consider export fluxes out of photic layer (especially using ^{234}Th) techniques) and those concerned by the measurements of biogenic matter in deep waters and at the water-sediment interface. To take into account the processes that control the fluxes of remineralisation and recycling in the « twilight » zone (100-1000m) should be a high priority for future programmes.

Question 3 : What are the major features of spatial and temporal variability in the physical and chemical environments and key biotic factors ?

The classical view of latitudinal bands of contrasted marine environments around the Antarctic continent, although still alive has been strongly shaken as numerous SeaWIFs images reveal the importance of west-east gradients. This has likely to do with eastward aeolian transports of trace-metals, from the southern tip of the American continent and from subantarctic islands.

Different from the SubTropical and SubAntarctic fronts the real significance of the Polar Front as a physical, chemical and biological frontier is now questioned. The importance of the physical-biological coupling at mesoscale has been demonstrated both from SeaWIFS images and from circulation models (e.g. OCCAM).

Since the begining of the 1990s numerous sophisticated biogeochemical models have emerged, including several nutrients and micro-nutrients, 2 to 3 phytoplanktonic species and 2 kinds of grazers. Nonetheless they still remain preliminary tools to account for the complexity of the merry-go-round Antarctic ecosystems, characterised by the sequestration of limiting nutrients by hard or soft-armoured species (e.g. large diatoms and colonies of *Phaeocystis antarctica*). Large scale distributions of krill and salps (the two major large grazers of phytoplankton) are now available showing the two grazers usually inhabit in different environnments. Attention is to be put on the role of key species in the key ecosystems, on the community structure and on the dynamics of the higher trophic levels, if we want to improve the models outputs in terms of carbon retention and/or export.

Several data sets are now available regarding the seasonal variations of total organic carbon (TOC) *vs.* latitude as well as those of the bacterial production in surface waters. High concentrations of semi-labile TOC have been evidenced in frontal areas. They represent high levels of CO_2 potentially produced through bacterial respiration.

Question 4 : What is the effect of sea ice in and to the Southern Ocean ?

This question makes SO-JGOFS unique among the JGOFS community. The seasonal waxing and waning of sea ice around Antartica is one of the largest seasonal signal on planet Earth. During the first years of SO-JGOFS, with the help of satellite remote sensing a lot of attention has already been put on the specific role of ice on the CO_2 fluxes : on the one hand the large extent of sea ice in winter clearly precludes gas exchanges (including CO_2), but on the second hand the sea ice (in its various kinds) can support intense biotic activity especially in the coastal and continental shelf zone, with much implications for the biological CO_2 fluxes. Moreover, the ice edge interacts with the various frontal boundaries in the Southern Ocean, although there is considerable longitudinal variation. For example, north of the Ross Sea, the maximum ice extent is nearly coincident with the Polar Front whereas in the area near Kerguelen Island, sea ice remains poleward of the Polar Front by about 10° of latitude. The interactions of these fronts and the ice edge may have significant physical biogeochemical impacts.

The sea ice has definitely to be approached as a unique system. During the last 5 years a lot of attention has been put on the Ross Sea and on its interannual variations with regards to primary productivity. Interannual variability may be linked to ENSO. In addition to the classical export pathway based on diatoms, the carbon export flux associated with *P. antarctica* represents another important pathway for carbon sequestration. Because blooms of *P. antarctica* cause intense DMS emissions the role of *P. antarctica* may be more important than previoulsy thought with respect to the Southern Ocean biological pump. Care should be taken that the export of *P. antarctica* cell carbon and associated mucilageneous biomass is quantified. Large deviations from the classical Redfield ratios have been reported, which has much implications for modellers. We still have to fill in the gap of the linkage between the ice and the adjacent water column ecosystem to better understand the dynamics of the Seasonal Ice Zone.

Question 5 : How has the role of the Southern Ocean changed in the past ?

It is clear the biogeochemistry of the Southern Ocean is very sensitive to climate change, but depending of the proxies the authors refered to, much disagreement is remaining about what happened to the biological pump of CO_2 during the past, and especially during the Last Glacial Maximum (LGM). To reconcile contradictory interpretations multiproxies studies that take into account the glacial boundary conditions of wind stress, ocean circulation, sea ice extension and temperature are encouraged.

One major debate is about the variations in the location of the fronts in the Antarctic Circumpolar Current. Because this location appears to be constrained by the seafloor topography the northward shift of e.g. the Polar Front during the LGM is now questioned. One scenario considers that during the LGM, compared to the modern ocean, the primary productivity increased north of the PF due the northward penetration of nutrients (especially of silicic acid) and to enhanced aeolian inputs of iron. But south of the PF less production of diatoms is envisaged, the change in nitrate utilization being explainable by enhanced production of *Phaeocystis* which left no record in sediments. To get better paleoreconstructions a convergent focus of modern ocean scientists and of paleoceanographers is needed, especially on the variations of opal/Corg, N/P, N/C, and on the role of *Phaeocystis* for C export flux.

Question 6 : How might the role of the Southern Ocean change in the future ?

We already have some indications the biogeochemistry of the modern Southern Ocean is changing. Global physical-biogeochemical coupled models are now available indicating the Antarctic Ocean might become the main oceanic sink for atmospheric CO_2 if atmospheric CO_2 concentration continues to increase exponentially. Nevertheless this capacity could be counteracted by an induced stratification of Southern Ocean in a warming climate. To improve our predictive capacity however coupling models with observations is a high priority. We first need to identify the key parameters (time + space) showing maximum sensitivity to change in models (considering both regional and global response) ; this goes through designing observational strategies to test model predictions, detect the global climate change, and understand the linkages. Second we need improved understanding and parametrizations for accurate model predictions, especially to better know : (1) how do ecosystems structures (taxonomic groups) respond to changing physical and chemical boundary conditions associated with ACWs and global warming, and (2) how do ecosystems responses influence climate through « feedbacks » associated with altered carbon fluxes and altered sources and sinks of other climate-sensitive substances (e.g. DMS).

The session of the Symposium related to Question 6 as well as the Round Tables were designed to stimulate discussions on future research needs, ranging from the synthesis of the JGOFS results in the near term to the design and operation of Ocean Observing Systems and Process Studies further into the future.

Round-Table 1 : Tools and Instrumentations :

During the last ten years the development of chemical and optical sensors has been noticeable. This will make easier the continuation of time-series stations in the Southern Ocean, which is firmly recommended by the Southern Ocean – Synthesis Group. An international project group including Australian, Italian, French, Japenese, and possibly US scientists has been identified (coordination Tom Trull, ACRC, Hobart).

Round Table 2 : Modelling and Process Studies :

The focus was on the flow of carbon from the air-sea interface into the ocean interior on seasonal and annual time-scales. From a JGOFS perspective the Southern Ocean is an excellent place to work because it contains the whole spectrum of limitation on biological production. Gaps to be filled in during the near future : transfer of carbon between the euphotic layer and 1000m, processes supplying bio-available Fe to the photic zone ; $CaCO_3$ production (i.e. in the SubAntarctic Zone) ; grazing impacts (i.e. mesozooplakton, salps vs. krill) ; continuation of time-series stations.

Model-Data interactions : The JGOFS community must ensure that all the data is archived and available to modellers ; pCO_2 data provides valuable information on the spatial and temporal cycling of carbon in the upper ocean and all the data needs to be available.

Future : Data assimilation models will provide improved circulation that will advance modelling effort. But biogeochemical models should be included in this effort to improve BGC models and the circulation models (i.e. SeaWIFS data contains circulation information).

Round Table 3 : Deviations from Redfield ratios *:*

Large variations of C/N/P ratios compared to Redfield have been reported. They clearly are related to variations in phytoplankton species dominance, a key point that is relevant to modellers. However, although many studies find consistent evidence for P /N and P /C uptake ratios above Redfield values during early stages of diatom-dominated blooms, the stoechiometric composition of material exported to depth is less well constrained by observations. Future studies must determine if the P/C and P/N ratios of export flux are also much greater than Redfield values, or if the export ratios are much closer to Redfield values because of preferential regeneration of P before particles sink out of surface waters.

Future Programmes :

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