Report for the weeks 12th January to 1st February 2009

The search for a suitable eddy and start of the experiment

The first two weeks were devoted to the search for a suitable eddy in which to carry out the experiment and the third week to start it. A small-scale experiment such as LOHAFEX has to be carried out in a suitable container stable enough to prevent it from being dispersed in the vast ocean and deep enough to follow the effects of fertilization of the surface layer through the underlying water column down to the deep sea floor. These are tall orders in an oceanic region as restless and deep-reaching as the mighty Antarctic Circumpolar Current (ACC). Two previous experiments had been successfully conducted from Polarstern in closed, rotating cores of stationary eddies extending down to the bottom formed by meandering bands of strong currents caused by hydrographical discontinuities known as fronts. These eddies were located in the eastern Atlantic south of Africa and had been found without much trouble, but, as hindsight shows, with a huge portion of good luck. We now intended to study the response of a plankton community in an eddy of the more productive western South Atlantic. Daily satellite altimeter images of the region north of South Georgia showing decimetre-scale variations of sea surface altitude had always been studded with eddies appearing as blue and red blotches in a flat sea of green: dimples and pimples respectively, across the face of the ocean (see picture in previous report). We had selected a site where a blue eddy with colder water in the centre, hence spinning clockwise, appeared regularly in previous years in a fold of the bottom topography and stayed there for prolonged periods. However, this year the eddy field is much more dynamic with the red pimples and blue dimples jostling with each other for space.

A physicist working in Paris had recently developed a numerical analysis based on data from satellite altimeter observations. He used methods from the chaos theory toolbox including Lyapunov exponents for application to the study of eddies appearing and dispersing in altimeter images. He was delighted by the opportunity to tailor his arcane models to our needs in the Southern Ocean and worked hard to test the various eddies in our study area. His model's depiction of the flow fields shaping the structures of eddies is an eye-catching new way of visualising the dynamic face of the ocean. The results of his carefully prepared analyses reached us 5 days after sailing and were not encouraging. He compared the EIFEX eddy we had mapped in 2004 with those in our envisaged study area and showed that the closed core of the former had been an ideal case, in striking contrast to those north of South Georgia which all had leaky cores. In the light of his discouraging prognosis, we inspected an eddy, similar to the EIFEX one and along the same latitude (48° S), which lay on the way. It was located at the eastern side of the plume of higher productivity, signalled by the presence of spores of coastal diatom species in the underlying sediments, which emanates from the Antarctic Peninsula and stretches across the western South Atlantic.

As mentioned in the first report, we found that silicic acid, the raw material of diatom shells, had been almost completely used up to a depth of 100 m by previous diatom blooms. Even the EIFEX bloom dominated by thick-shelled diatoms, which had grown during the late summer, did not manage to deplete silicic acid to these low values. It is well established that silicic acid is exhausted in the northern ACC by mid-summer due to the fact that diatoms here have a smaller supply at their disposal to start with in the spring. Further south the spring supply is much higher so the diatoms (the major group with an obligate demand for this element) do not manage to use it all up by the time winter deep mixing commences. However, in the Southwest Atlantic Sector silicon depletion extends much further south due to its higher productivity, so the closed core of this eddy evidently belonged to this sector.

The composition of the plankton community confirmed that it represented a late stage in the seasonal cycle. The diatoms comprised thin-shelled, needle-shaped species of the genera *Rhizosolenia* and *Proboscia*, some of which reach high densities in coastal waters, and there were also large numbers of a non-toxic dinoflagellate belonging to the genus *Ceratium* which is characteristic of late summer blooms along the coasts and open ocean of the northern Atlantic but has not been observed, to our knowledge, at these concentrations so far south. Another remarkable feature was the large number of zooplankton dominated by the crustacean group known as copepods which are the major link in the food chain leading from unicellular plankton to larger animals such as fish. The adults of the species present spanned a size range from 0.2 to 2 mm but the large numbers of juvenile stages of all species indicated that their parents must have enjoyed an abundant food supply some weeks to months previously.

After confirming that this eddy (eddy 1) had low current speeds in its centre and hence contained a closed core suitable for the experiment, we proceeded westward to the eddy field in our pre-selected study area north of the island of South Georgia, but made a detour to the south for two reasons. One was to ascertain the nature of the eddies to the northeast of South Georgia, the other was to visit one of the large icebergs which our meteorologist had been pointing out in satellite photographs during his daily, entertaining briefings. They were moving in a north-easterly direction and the biggest was over 15 km in length but too far to the south, so we chose to intercept a smaller one located at 49° S. We had already encountered so many ice bergs by now that their presence had become routine but, although some were as big as cathedrals, the effects of their melt water on the surroundings were minor. But we hoped to be able to record the influence of melt water and the iron-containing dust in it, in the surroundings of a larger iceberg.

The ice field around a crumbling ice berg

During the night we passed through a 45 km stretch of lower salinity water (<33.4 compared to the surroundings of 33.9) which was clearly the trace of a melting ice berg. On approaching the position of the selected one, we were surprised to find that it was a collection of smaller icebergs in an extensive field of densely packed ice rubble reminiscent of sea ice but, instead of flat floes, irregular shaped lumps in the metre-size range stretched around us. We spent a day mapping the “lake” of fresher but colder water that had formed in the middle of the open ocean, trying to ascertain how we would sample it and how long the lake would last. We decided to first take a station as deep inside the ice field as possible. A normal ship would have been dangerously dented by now, but for Polarstern these were mere crumbs of ice, easily nudged aside as she passed majestically through the icy landscape.

The sensation of being completely surrounded by ice was a magic moment for the crowd that had assembled on deck, a breathtaking experience for the novices, for many of whom this was the first contact with natural ice. The crowd first whooped with excitement but soon lapsed into a meditative silence commensurate with the grandeur of the surroundings. The wind had died down, the skies were grey, and a light fog added to the eerie atmosphere. We found ourselves whispering to each other, so awed were we by the ice around us. But all too soon activity broke out as Polarstern rumbled to a halt at a safe distance from the many ice bergs and her powerful bow thrusters (propellers located at the bow and aft of the ship allowing sideward propulsion) blew aside the ice rubble so that we could start the station. Our chief instrument, the CTD rosette, was lowered and a group gathered in the winch control room around the monitor on which the profiles of its various sensors appear. These record the following properties of the water column through which it is lowered: temperature, salinity, oxygen, chlorophyll fluorescence (a measure of the amount of phytoplankton in the water), turbidity (a measure of the cloudiness of the water, i.e. the total amount of particles suspended in it). These instruments are our sense organs and we have trained ourselves to read structures in their profiles. On the way up, 12 L cylindrical bottles attached in a rosette of 24 around the sensors are closed individually at desired depths to obtain water samples on which a host of other properties are measured by scores of instruments in the labs.

The temperature and salinity profiles showed that the melt-water influence reached down to 25 m. This “lake” of fresher, hence lighter water was stabilised deeper down by its colder temperature which, not surprisingly, was close to the freezing point at the surface. The cold water cooled the air above it and by dusk a dense fog descended on the scene. Since the ice bergs around us were difficult to distinguish on the radar screen due to reflection from the ice rubble, and the dense fog rendered them invisible, we decided, for safety reasons, to leave the station after taking a net haul which again was full of copepods. We spent the night steaming round the periphery of the crumbled ice berg taking shallow profiles with the CTD with the intention of repeating a few more stations inside the ice rubble during the day. However, the fog remained so we decided to continue on our mission after taking a station some distance from the melt-water lake as a baseline.

The search continued

Silicic acid concentrations were even lower than in eddy 1, with fewer diatom and more *Ceratium* cells comprising the phytoplankton. In order to ascertain how far south the low silicic acid values reached, we aimed for an eddy located at 52°S for comparison with those to the north. Our modeller in Paris, whom we now called the “Oracle”, found this one to be a good candidate, so at the least we would acquire information to test his calculations. We were measuring nutrient concentrations continuously in the water piped through the ship’s intake system and found extremely low silicic acid concentrations everywhere. Clearly, we would encounter more or less the same type of silicon-starved plankton community throughout the region we had selected for the experiment. This finding was reassuring as it meant that the results of our experiment would be applicable to a vast region of the Southwest Atlantic.

On our way to the eddy field in the region north of South Georgia we aimed our transect so as to cut through a blue (eddy 2) and a red blob (eddy 3). The oracle’s maps showed that the group of eddies had leaky cores and indeed our current measurements through eddy 2 clearly demonstrated that strong currents flowing in opposite directions were closely juxtaposed, i.e. there was no closed core with low current speeds in the centre. So we could trust the Oracle’s predictions that the eddies in this region were very dynamic, hence not suitable for a long-term experiment such as ours. A station taken in the centre of eddy 2 revealed a shallow mixed layer only 25 m deep which also explained the unusually high surface temperatures of the region (well above 10° C). The density profile (a function of temperature and salinity) exhibited “steps” in the deep water column indicating over-layering of different water masses. This meant that the surface eddies were not deep-rooted, which in turn explained their dynamic behaviour in the satellite images.

Yet another reason not to carry out the experiment in the pre-selected region were the high chlorophyll concentrations (1.2 mg Chl m^{-3}) in the shallow surface layer in the centre of eddy 2, i.e. in the innermost band of currents. These concentrations were twice as high as expected and in the range of concentrations our fertilization would induce in this type of plankton community. Satellite images showed even higher concentrations to the North. There were few ice bergs here, so the iron must have come with wind-blown dust probably emanating from Patagonia. The patchiness in plankton abundance and composition was also observed by microscopic evaluation of surface water sampled by the ship's intake system during the long, northward transect. Although the community-type was basically the same, there were differences in the relative proportions of species contributing to the total assemblage of phytoplankton cells. Explaining regional and seasonal patterns in the distribution of phytoplankton species is one of the major challenges facing bio-oceanography because one can expect different species to have different effects on the food web they support and ultimately the global carbon cycle. At least this is our experience from land ecosystems where everybody can see that different plant species (e.g. deciduous or evergreen tree species) can have different effects on their environment, including biodiversity.

Since the beginning of the last century many research expeditions, including a series of Polarstern cruises, have carried out systematic surveys of the distribution and abundance of planktonic species in relation to the physical and chemical properties of the environment in various regions of the Southern Ocean. The data gathered from these cruises has led to formulation of various hypotheses regarding the factors shaping the species composition and their possible feedback effects on the chemistry of their environment, including the carbon cycle, that are difficult to test with further field observations. This is because information on the past history of a water mass harbouring a particular species assemblage is always missing. This information can only be acquired by experimental manipulation of a given assemblage in a natural manner, because one can record the initial conditions and then follow the processes leading to shifts in the community driven by rising and then declining productivity and compare them with processes in the surrounding, unaffected waters.

Some notes on phytoplankton

The phytoplankton species contributing to the high biomass in eddy 2 comprised mainly small cells belonging to an algal group responsible for a significant share of the ocean`s productivity and known as haptophytes ("grasping plants"). The name comes from a lasso-like appendage, which they can extend and curl, located between the two flagellae with which they swim in the direction they choose. The cells are only 5-10 micrometers (1 micrometer = 0.001 mm) in diameter and most of the cell is filled with the chloroplasts in which photosynthesis takes place, qualifying them for inclusion in the phytoplankton or plant plankton. However, they can also feed on particles such as bacteria which they capture with their lasso and which would qualify them for inclusion with the unicellular "animals" or protozoa. In addition to their two distinctly different modes of nutrition (known as mixotrophy or mixed nutrition) the complex life cycles of different haptophyte species clearly demonstrates that small is not necessarily simple. The different life cycle stages have radically different effects on the chemistry of their environment, so it is necessary to study them further because of their bearing for the outcome of an experiment carried out with this particular community.

The haptophytes comprise several groups of which the coccolithophorids or chalk algae play a major role in the global carbon cycle because they are covered with intricately patterned, minute scales made of calcium carbonate (chalk) which subsequently sink and settle on the sea floor where they form thick deposits over geological time scales. The famous chalk cliffs of Dover and the island of Rügen in the Baltic were formed by these algae. Although they bury carbon in the sediments, the effect of chalk algae on sea water is quite the opposite: calcium carbonate deposition in the scales leads to a decrease of total dissolved inorganic carbon (the sum of CO_2, bicarbonate and carbonate ions) but at the same time to an increase in concentration of free dissolved CO_2 which is quite counter-intuitive. By the way, this rule also applies to the carbonate skeletons and shells of corals and molluscs. If the excess CO_2 molecules are incorporated into organic matter, the net effect on the CO_2 equilibrium between sea water and atmosphere is close to neutral, but if the chalk scales sink out of the surface layer and the organic matter is digested by microbes and zooplankton within it, then the excess CO_2 outgases to the atmosphere. Extensive blooms of chalk algae are a regular feature in the North Atlantic and appear as white streaks and splotches in satellite images. They are also present in the South Atlantic but are not strong enough to be seen in satellite images. However, if iron fertilization encourages growth of chalk algae in the iron- and silicon-limited northern band of the ACC, the net effect would result in a release of CO_2 to the atmosphere, instead of the other way round.

Chalk algae were abundant in the warm waters of the dynamic eddy field and contributed substantially to the bloom in the centre of eddy 2. Since the factors leading to their blooms are poorly understood, we would have loved to carryout our experiment there to see how they reacted. But an experimental patch as small as ours in such an unstable eddy would soon be pulled into filaments and disappear within a few days. Clearly this region was not suited for a long-term experiment such as we intended carrying out.

Luckily, the plankton community in eddy 1 we had inspected further east was of the same type but in an earlier stage of succession than those of the region north of South Georgia. It was located at the same latitude as the EIFEX eddy but much further to the West. Its much lower silicic acid concentrations clearly demonstrated that it was well within the productive south-western zone of the South Atlantic. The abundance and composition of the zooplankton were also very similar throughout the region we had sampled so far: the same species of copepods dominated the biomass, salps were conspicuously absent and a few chaetognaths but abundant amphipods represented the predators. The only apparent but intriguing difference was in pigmentation of the copepods which were transparent with only a few red spots in the first eddy, but further to the West the same species had brilliant red antennae and another species had an orange girdle.

Start of the experiment

We headed back eastwards to eddy 1 and were sped on our way by strong westerly winds and currents. We arrived there on the 24th January. The current meter profiles of the upper 200 m confirmed the accuracy of the altimeter image and a transect of CTD profiles showed a dome of cold water in the eddy centre with very low current speeds – the closed, stable core – but the surface layer appeared to be more dynamic. We deployed a buoy equipped with positioning instruments as close to the centre as possible and followed its track while we carried out transects to obtain more information on the dynamics of the surface layer.

Since we had identified the centre of the eddy with reasonable confidence by midday of the 25th January, we started the first baseline station which lasted well through the night. In the evening of the 26th the decision of the Federal Ministry of Research to allow the experiment to commence was delivered by telephone and announced to the scientific crew assembled on the working deck who broke out in loud cheers. Immediately after receiving the green light we filled both the two 6 m^3 tanks with 775 kg of iron sulphate powder dissolved in sea water and commenced fertilization the next day after completing the baseline station and deploying a second buoy two miles north of the first, where we now thought the true centre was. We also deployed 3 neutrally buoyant sediment traps that are programmed to stay at pre-planned depths, in this case one at 200 m and 2 at 450 m depth, and return to the surface after a given time period.

The iron sulphate solution was released through a hose trailing in the ship's propeller wash while she spiralled around the drifting buoy in widening concentric circles one km apart. Since the iron is rapidly taken up by the biota or converted into insoluble colloidal rust, the inert gas sulphur hexafluoride (SF_6) was continuously added in trace amounts to the iron solution in order to mark the fertilised patch as SF_6 can be measured at very low concentrations. A total of 480 g of this biologically inert gas is sufficient to mark the entire patch. A tank was emptied in about 2.5 hours and was filled by teams of scientists while the contents of the other was being released. Iron sulphate tablets are used to treat patients suffering from anaemia and we used the same quality grade sold in gardening shops and department stores for treating lawns. Nevertheless, the substance is converted into rust which stains clothing and large amounts of the dust can irritate eyes and nose so we took maximum precautions to reduce exposure to the minimum by having those doing the job wear protective clothing and masks. An area of 300 km^2 was fertilised with a total of 10 tonnes of iron sulphate which took 30 hours to complete. We administered only half the quantity originally planned because the mixed layer was only half as deep as expected.

The ship then returned to the central buoy where we repeated the measurements carried out at the baseline station (Day 0) to ascertain the initial response of the plankton community to the iron addition. As expected, there was no measurable response in most environmental properties confirming that we were sampling the same water column and that our instruments were working at a high degree of precision. As recorded in all previous experiments, the photosynthetic efficiency of the phytoplankton, measured with a Fast Repetition Rate Fluorometer (FRRF), increased significantly, indicating that their cellular machinery had been working below capacity due to iron limitation. Within the cell, iron atoms are involved in transferring energy and are an essential part of many organic molecules such as co-enzymes, so when iron becomes available, the cells are activated and can start synthesizing new molecules.

Just as land plants have adapted their needs to the water supply of their particular environment, so different phytoplankton species can be expected to be adapted to the iron concentrations of their environment. This has been shown for various diatom species that are adapted to either the high iron concentrations prevalent in coastal waters or the low ones of the remote ocean. Hence, the former species respond more strongly to iron input than the latter. However, their response also depends on the life cycle stage in which they happen to be when the iron input occurs. Our knowledge of the factors driving the life cycles of marine phytoplankton is restricted, indeed we are just beginning to recognise their role in shaping seasonal cycles, aided by the application of modern, molecular biological tools. Microscope examination of the plankton revealed the presence of many species commonly found in coastal waters, so we expect them to respond more rapidly than the typically oceanic species. We are closely following the species diversity and abundance of the phytoplankton assemblage using both microscopy and molecular tools as the bloom develops.

At the end of the station we sampled the sediments on the sea floor underlying the patch with a Multicorer and the larger zooplankton by towing a large net known as the Rectangular Midwater Trawl (RMT). The traps, which had surfaced close to each other in the meantime, were then recovered. Our next task was to carry out a long station in an unfertilized water column within the core but outside the patch which would serve as the first "out station". The water column properties were much the same at both sites. On Sunday we started mapping the patch with the towed undulating instrument called Scanfish which carries all the sensors in the CTD in addition to an FRRF. The buoys are within the patch and chlorophyll concentrations around them are rising. We are awaiting further developments with suspense.

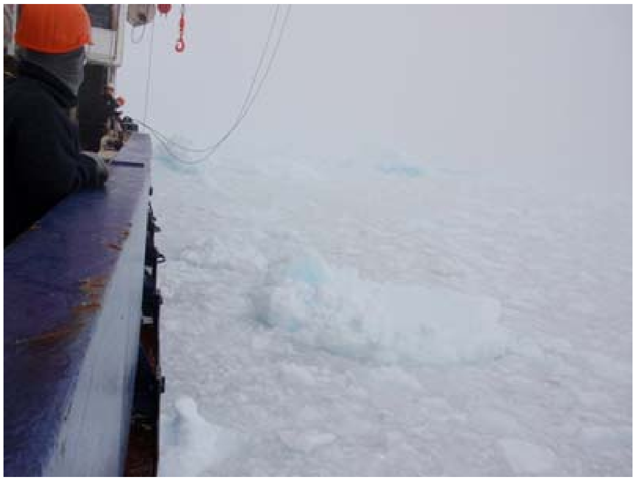
A celebration on board

The 26th January is India's Republic Day so it was celebrated with a flag-hoisting ceremony on the windy top deck followed by singing of the national anthem after which we retreated to the Blue Saloon to listen to short, but moving speeches and toast each other with orange juice and carrot halwa prepared by the scientists. The head stewardess had decorated the mess with buntings of Indian flags she had painstakingly prepared for the occasion while we enjoyed Indian vegetarian dishes specially requested for the occasion. The Indian contingent had prepared a cultural event celebrating India's diversity to which the crew was invited. It started with an introduction to unique Indian traditions delivered in English and German followed by songs and poems rendered in all the languages represented on the ship. It started with Hindi, then Rajasthani and moved southward with Bengali, Marathi, Oriya, Konkani, Kannada, Telugu, Malayalam and finally Tamil. In between a Kathak dance performance received resounding applause. The crew were charmed.

We are currently mapping the patch with the Scanfish and underway measurements of SF_6 and other properties of the surface waters.

With our best wishes from a ship full of excited scientists in excellent humour looking forward to the developments ahead,

Wajih Naqvi and Victor Smetacek



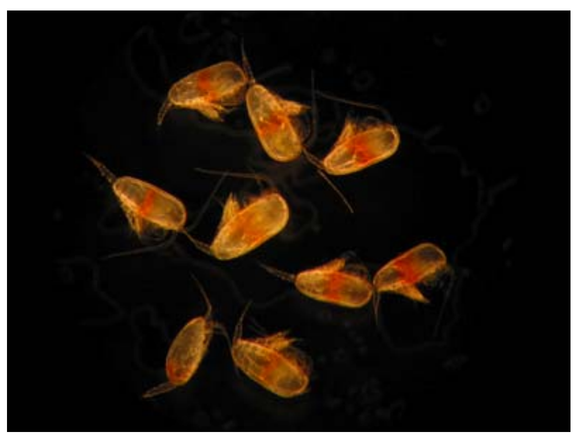
1. The ice field formed by a crumbling ice berg.
Photo: V. R. Sundereswaran, CCMB / Alfred Wegener Institute

2. The CTD rosette being lowered in the water of the ice field with ice berg in the background.
Photo: V. R. Sundereswaran, CCMB / Alfred Wegener Institute

3. The CTD rosette is being tapped on deck.
Photo: M. Ettlin, Alfred Wegener Institute

4. The phytoplankton species *Ceratium pentagonum* from the ice field with diatoms and juvenile copepods in the background.
Photo: M. Montresor, SZN / Alfred Wegener Institute

5. The copepod species *Calanus simillimus* with red antennae north of South Georgia.
Photo: G. Mazzochi, SZN / Alfred Wegener Institute



6. The smaller copepod species *Clausocalanus laticeps* with orange bands round its midriff.
Photo: G. Mazzochi, SZN / Alfred Wegener Institute

7. Singing the national anthem after hoisting the flag on the Indian Republic Day (January 26th).
Photo: M. Ettlin, Alfred Wegener Institute