Weekly report no. 9 EIFEX (ANT XXI/3) RV „Polarstern“ 22 March 2004

What an exciting and rewarding experiment this has been! The search for a suitable eddy, the bold decision to try out the second one, the toil of fertilising the plankton, the anxiety and the patience involved in locating the rotating patch and finding its hot spot, the exhausting, long stations, the heaving ship that kept us from our much deserved sleep, crowned finally by the satisfaction of seeing our „crop“ sink out into the briny deep. We all worked to the limits of exhaustion supported by a crew that fulfilled every wish as it arose. It has all worked out perfectly and we are leaving our patch without regrets. We could not have achieved more and are satisfied. What a wonderful feeling!

EIFEX was the first experiment that was able to study the fate of an iron-fertilised bloom in detail. The rate at which the diatom chains from our bloom sank through the water column exceeded our expectations by far. We had concentrated our efforts on the upper 500 – 1,000 m layer and had planned to take only 5 CTD profiles down to the bottom during the entire cruise to determine the deep structure of our eddy, but last week the CTD went down to the bottom at 3,800 m depth many times, taking profiles of the sinking diatom aggregates as they traversed the deep water column. The last cast was devoted to the layer just above the bottom after we noticed how much the turbidity had increased in it since the experiment was started. Microscopic examination of an enriched water sample from 15 m above the bottom revealed innumerable chains and cells of the diatoms from our bloom. We knew they were from our bloom because their filigree structure and long, pointed spines were still in perfect condition. As these dissolve within a few weeks we were looking at very fresh material, yet untouched by zooplankton. There also were the missing Chaetoceros from our bloom, together with many cells of other thin-walled species. Most were empty but some still had cell contents although these were generally disintegrated. The flow cytometer – an instrument that counts and measures particles flowing past a laser beam – even found fluorescing cells, i.e., some still contained chlorophyll.

Together with the intact chains and cells was also debris of crushed diatom shells loosely adhering to one another that clearly represented material that had gone through the guts of zooplankton. The sinking chains must have aggregated with this broken-up faecal material during their descent and dragged their particle load into the deep. Prior to this event thorium measurements in the bloom, which provide an estimate of the amount of particles sinking out from the mixed layer, indicated that no losses were occurring. So the faecal material produced by the grazing zooplankton was being retained. However, once the mass sinking commenced, some of the detritus accumulating in the mixed layer, possibly in the form of loose flocks, went down with the diatoms. In short, although the particle rain consisted mostly of silica cell walls, some carbon had been transferred to the deep as well. The amount involved will be determined later at home.

The last station outside our patch showed that the same process we had observed in our bloom had occurred here as well but at a much smaller magnitude. The populations of Chaetoceros species that had dominated the phytoplankton till recently were gone here as well and the same species as in our bloom now dominated the sparse phytoplankton assemblage. There were also blips in the transmissometer profile showing more particles in the deep-water column than before, but this drizzle was nothing like the heavy snowfall under our bloom. So the mass mortality and sinking out of almost all the Chaetoceros and many other thin-walled species also occurred out---side our fertilised patch. But because there was more biomass, the rainfall was heavier. Although the causes of mortality are not yet known, the phenomenon was clearly part of the replacement of species typical of planktonic (pelagic) ecosystems everywhere, from lakes to the open ocean. This seasonal species succession has been known for over 150 years but the driving forces and the evolutionary advantages accruing to the species have not yet been satisfactorily explained. It is interdisciplinary experiments like ours that will shed light on this age-old problem because it can only be understood in the larger context of environmental factors that control the growth rate of the algae (light, iron, nutrients etc.) and the depre---da-tions of pathogens, parasites and grazers that control the mortality rates of the different species.

Another factor that results in the fallout of empty cells in diatoms is sex. This is because cell division in diatoms results in decreasing size of daughter cells. At a certain size, a sexual phase is initiated and the cell contents are converted into gametes (many sperms but one egg per cell) which leave behind empty cell walls. The fertilised egg then expands and attains the maximum size for that species before making a new cell wall, after which the cycle of vegetative cell division is repeated. The flam----boy-ant Corethron with its crowns of long spines radiating out like the spokes of an open umbrella, is a particularly sexy species because its size reduces rapidly with each division. Many empty half-cells of this species were present in the bottom-near layer, indicating that the species had entered a mass sexual phase in the bloom and contributed to the fall out of silica from the surface layer. The death of the other species, however, was certainly not a sexual event.

The long, thin but tough, rod-like cells (2 mm long, 0.006 mm wide) of the thick-walled diatom Thalassiothrix antarctica („Antarctic sea hair“) re----mained in the plankton after the fall of Chaetoceros and its asso-ciates. The masses of diatoms caught by the zooplankton nets were annoying because it was difficult to retrieve undamaged copepods caught in them. However, the mats of glass wool made by the fibre-like Thalassiothrix cells that cling together by rows of sharp barbs on their surface, make the sorting of zooplankton samples a nightmare. The tough mats also indicate that the cells of this species are not likely to be a favourite food item of the grazing copepods which must prefer more accessible food like the smaller Chaetoeros species we expected to dominate the bloom. The fact that the numbers of the less protected, smaller species declined in the second half of the experiment suggests that they were selectively grazed down by the zooplankton population that increased during the bloom.

Other common species that continued growing in the patch and outside were Pseudo-nitzschia species and Fragilariopsis kerguelensis (Fkerg). The needle-like chains of the former superficially resemble a Thalassiothrix cell and are probably also grazer resistant. Fkerg cells are boat-shaped and reinforced with thick ribs that make them extremely resistant to crush-ing. This species, together with Thalassiothrix, contributes about 90% of the siliceous sediments accumulating under the ACC, which also happens to be the largest single sink of this element in the oceans. Why so much silica accumulates in a region of iron-limited, low productivity has puzzled oceanographers for long. The processes we followed during the bloom now indicate that it is indeed selective grazing of the faster-growing, less-defended species that leads to dominance of the giant diatoms with their thick silica walls. The latter contain up to six times more silica per carbon than the thin- shelled species, so it is not surprising that the underlying sediments are carpeted with the shells of these robust diatoms. Ultimately, selective grazing by zooplankton is the reason for the heavy silica rain in the ACC.

The acoustic surveys revealed that the copepod population in the patch had increased significantly relative to the outside. As these minute animals grow slowly in cold water the explanation is that they had congregated inside the patch by modifying their patterns of daily vertical migration. When they find more food, copepods decrease the depth at which they spend the day. Since deeper layers move more slowly than upper layers, the higher up they stay, the better they are retained in the food patch. This be-----haviour has been suspected before but our data provide evidence that it does indeed happen. Another important finding is related to the salps that are widely regarded as food competitors of the copepods and krill that form the base of all important pelagic fisheries from sardines and herring to tuna and whales. Before fertilisation and in the outside water throughout our stay, salps were abundant in the net catches, but as the bloom pro-----gressed, their numbers declined and there were hardly any left at the end. We believe that this was due to the salps clogging in the dense bloom of spiny diatoms, meaning that these watery animals do not grow well in blooms, so cannot compete with copepods and krill under such conditions. In other words, salps do best at plankton concentrations typical of iron-limited waters, hence the reported increase in their abundance around Antarctica is an indication of decreasing productivity in these regions.

It is very likely that our bloom boosted growth of the copepods and local krill species but we do not know which carnivores will have profited from the production of this valuable food resource. There are few fish in the ACC and the large rectangular midwater trawl (RMT) that was hauled on several occasions when wind speeds were low enough to enable its de-ploy----ment, caught mainly the local krill species, chaetognaths (arrow worms) and amphipods. A few whales, seals and penguins were the only top predators apart from birds on the wing that we saw. There were many birds, partic-u---larly the giant wandering albatrosses and petrels of various sizes, that accompanied the ship. Although they feed primarily on zooplankton, their predation pressure is not likely to have been significant. Blooms of the magnitude we induced, albeit dominated by weakly silicified diatoms, form the basis of the rich animal life around coastal areas of Antarctica. Since iron fertilisation stimulated the entire plankton, including the zoo-plank--ton, it is tempting to suggest using this technique to enhance productivity in these regions or even extend their size to provide more food for endangered animal populations, in particular whales.

The overarching goal of this interdisciplinary cruise was to find out the fate of iron fertilised blooms in the ACC: is their biomass retained in the surface layer and converted back into $CO_2$ by bacteria and zooplankton or does at least a part of it sink out, thereby removing significant amounts of $CO_2$ from the atmosphere and storing it in the deep ocean. Most of the earlier experiments, including EisenEx, were too short to follow the fate of the bloom. So we were lucky in being able to observe also its demise phase. The above question has 2 dimensions, one related to the time scales of thousands of years during which the earth's climate changed through the cycles of ice and warm ages and the other related to the current threat of global warming at time scales of decades. Measurements of ice cores from Antarctica and Greenland have shown that $CO_2$ concentrations are strongly correlated with temperature but the cause-and-effect relationship is not yet known. Values during glacials reached a low of 180 ppm (0.018%) but increased to 280 ppm during the warm periods. These were the values prevailing till about 150 years ago, but today's values are at 373 ppm and steadily rising at 1.5 ppm per year because of fossil fuel burning. But where did the $CO_2$ come from and where did it go in the course of the ice age cycles?

The amount of carbon in land plants today is about equivalent to that present as $CO_2$ in the atmosphere but forests during ice ages (including the tropical rain forests) were of much lesser extent because the earth was colder and drier. So actually even more $CO_2$ that was bound in plant biomass during the moist, warm ages, went missing during the ice ages. However, the ocean contains about fifty times more $CO_2$ than the atmosphere and hence is the most likely source and sink over these climate cycles. The ACC plays a special role here because it contains enormous amounts of nutrients that are not used due to iron limitation of the plankton. If all the nitrate in the surface water of the Southern Ocean were converted into plankton biomass, the amount of carbon fixed would amount to about 2 ppm. Over the course of tens or even hundreds of years a maximum of about 50 ppm could be transferred into the deep ocean. The late John Martin, who was the first to show that ACC plankton is iron-limited, suggested in his „iron hypothesis“ that increased dust input during glacials, documented in the same cores in which the $CO_2$ was measured, would have enhanced productivity of the ACC. On average dust contains 10% iron by weight, so Martin argued that a part of the carbon produced by the iron-fertilised plankton sank out of the mixed layer and was sequestered in the deep ocean. Geochemists challenge this view because evidence from ACC sediments deposited during the glacial period do not provide clear proof whether this actually happened, so the issue of ACC productivity is being hotly debated these days. The results of our experiment now provide support for the „iron hypothesis“ by showing that open ocean plankton blooms do indeed export carbon. This finding will help solve at least a part of the riddle concerning the whereabouts of a huge amount of carbon in the course of the climate cycles.

The other aspect of our experiment, one that has been reported widely by the press, is whether large-scale iron fertilisation will remove sig-nif-i---cant amounts of the excess atmospheric CO2 introduced by humans in the past 100 years, thus alleviating the threat of global warming. In other words, can a process which took many thousands of years in the past, be speeded up to do the same job within a few years? The answer is clearly no because the maximum amount that could be taken out per year is only about 10% of the annual human output. So it would be much more sensible to reduce fossil fuel consumption rather than compensate it by speeding up one of Nature’s regulatory processes. True, our experiment has shown that iron-induced blooms can behave much like natural blooms, i.e., they have the same species composition and excess algal cells sink out rapidly taking some of their carbon with them. But we need to analyse our samples first before drawing definitive conclusions.

The CO2 deficit in the hot spot of our patch amounted to 15 g C/m2 in the 100 m water column at the end. An equivalent amount of nitrate was taken up, but the giant diatoms took up much more silica than their coastal cousins. Total primary production of algae (the amount of CO2 converted into organic matter) was equivalent to about double the CO2 deficit. Bac---te-rial respiration of organic matter on a daily basis was equivalent to about half that produced by the algae during the bloom. So the 3 figures – the amount of nutrients taken up, the primary production and bacterial respira-tion rates fit rather nicely. Bacterial growth rates actually declined during the phase of algal mortality suggesting that not much of the organic matter released by dying cells was broken-down to CO2 by this group. Detailed budgets of the amount of carbon produced, grazed, broken down and exported to the depths will be made once all the samples have been processed.

So this ship of terrestrial aliens has found out several interesting as----pects about life in the vast spaces of the remote ocean. Some of the suspicions regarding interactions within one of its ecosystems that are of significance to geochemical cycles of our planet were confirmed. This interdisciplinary cruise of physicists, chemists and biologists has reaped a rich harvest from the experiment. RV „Polarstern“ is now on her way back to Cape Town. The temperature is steadily rising, the wind has dropped and the sea is calm. We are extremely grateful to the crew for putting up so bravely with their enforced sojourn in one of the most violent oceans of this world just because we wanted to do an experiment there. Despite the inconvenience of working on a constantly heaving ship, they were always smiling and went out of their way to help us, regardless of the weather conditions. We are deeply grateful to them.

Best wishes from a ship looking forward to standing on terra firma and enjoying the sights, sounds and smells of land again,
Victor Smetacek