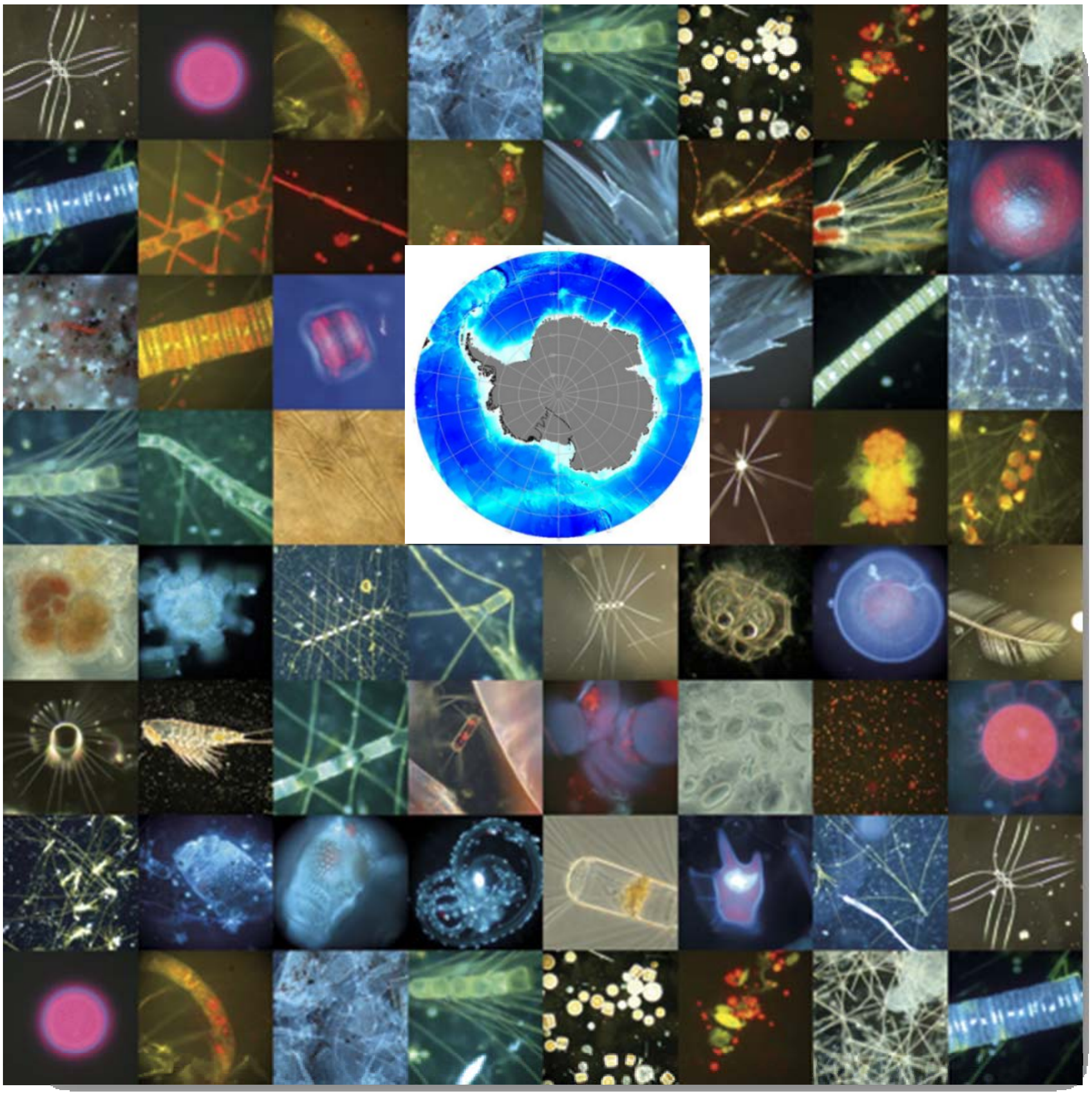
The Iron Wedge and a Climate on the Edge

The potential for artificial iron fertilisation of the Southern Ocean

as a viable carbon dioxide mitigation strategy



Mosaic of microorganisms found in an algal bloom in the North Pacific Ocean. Organisms featuring in the include phytoplankton, faecal pellets, marine detritus and a range of zooplankton. Photo collage modified from collage by Mary Wilcox Silver. Sourced from http://www.whoi.edu/oceanus/viewImage.do?id=59692&aid=35668.

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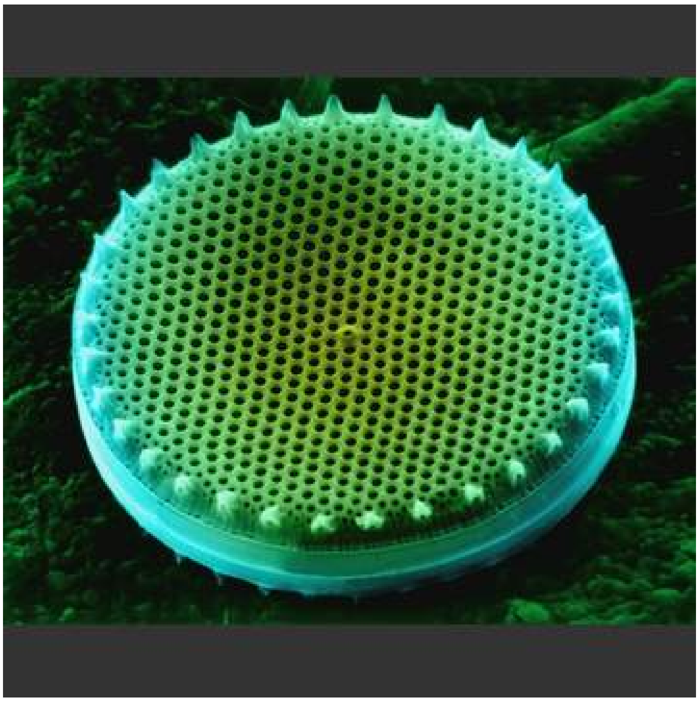

A typical saltwater centric diatom skeleton. These diatoms are prolific in the algal blooms of the Southern Ocean. Sourced from http://www.astrographics.com/GalleryPrints/Display/GP2131.jpg

Introduction

Although it still remains a misunderstood concept amongst the majority of the world's population, 'climate change' is a term which sticks in the minds of people from all walks of life. Scientists have proven that CO_2 levels in the atmosphere are increasing due to anthropogenic activity, although it remains uncertain just how much of an effect this increase may have in the future, due to the lag time associated with the increase and the consequent response.

Countless mitigation schemes have been put forward that could be used either to cut down the amounts of CO_2 entering the atmosphere, or alternatively remove significant amounts of CO_2 using the worlds natural carbon sinks. Terrestrial ecosystems are thought to be the largest sink, fixing 1 – 2 tonnes of carbon per km^2 annually through photosynthesis (Myers and Kent 2005). In the past, it has been assumed that oceans have a minor role to play in the carbon cycle, contributing only to small carbon fluxes. It has since been proven that the ocean has the potential to hold up to sixty times more inorganic carbon than the atmosphere (Bathmann et al. 2000). The ocean's role in the carbon cycle is illustrated below.

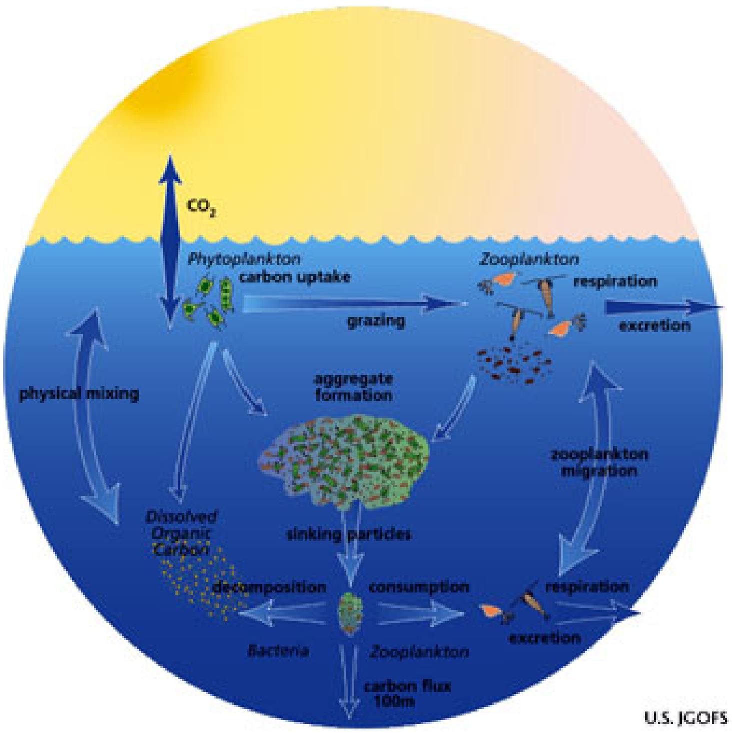

Figure 1. The Ocean Carbon Cycle. Phytoplankton takes up CO_2 absorbed into surface waters from the atmosphere. Zooplankton such as krill and salps graze on the phytoplankton, excreting organic carbon into the water column where it is either regenerated, or exported through the sinking of faecal pellets or the death of blooms. Export is desirable as it results in the sequestration of carbon into benthic sediments, removing it from the atmosphere for decades or even centuries. Figure sourced from www.uri.edu/images/carbon03.jpg

The sequestration and drawdown of CO_2 from the atmosphere into benthic marine sediments is an idea which has arisen following the acknowledgment of the marine ecosystem as an important player in the carbon cycle. This can be achieved through the fertilisation of large areas of ocean with iron, a limiting nutrient needed for phytoplankton growth and photosynthesis. During photosynthesis, buoyant phytoplankton utilise CO_2 that has been absorbed into surface waters. When the blooms sink or are grazed by zooplankton, this carbon is removed from the surface waters where it cannot readily return to the atmosphere.

Pacala and Socolow (2004) note that in order to meet the recommendation that CO_2 levels in the atmosphere should remain at their current level (7 billion tons of carbon annually) for the next 50 years, several mitigation strategies need to be undertaken. They represent various strategies as 7 "wedges" of a triangle, whereby a wedge 'represents an activity that reduces emissions into the atmosphere....until it accounts for 1 GtC/year of reduced carbon emissions in 50 years' (Pacala and Socolow 2004) (Figure 2). This would result in a net reduction of carbon dioxide emissions of 25 Gt by 2054. Each mitigation wedge will need to be put into action in order for the emissions to be reduced to an acceptable level. Pacala and Socolow (2004) identify terrestrial carbon sinks as having the potential to exist as a wedge without much further research.

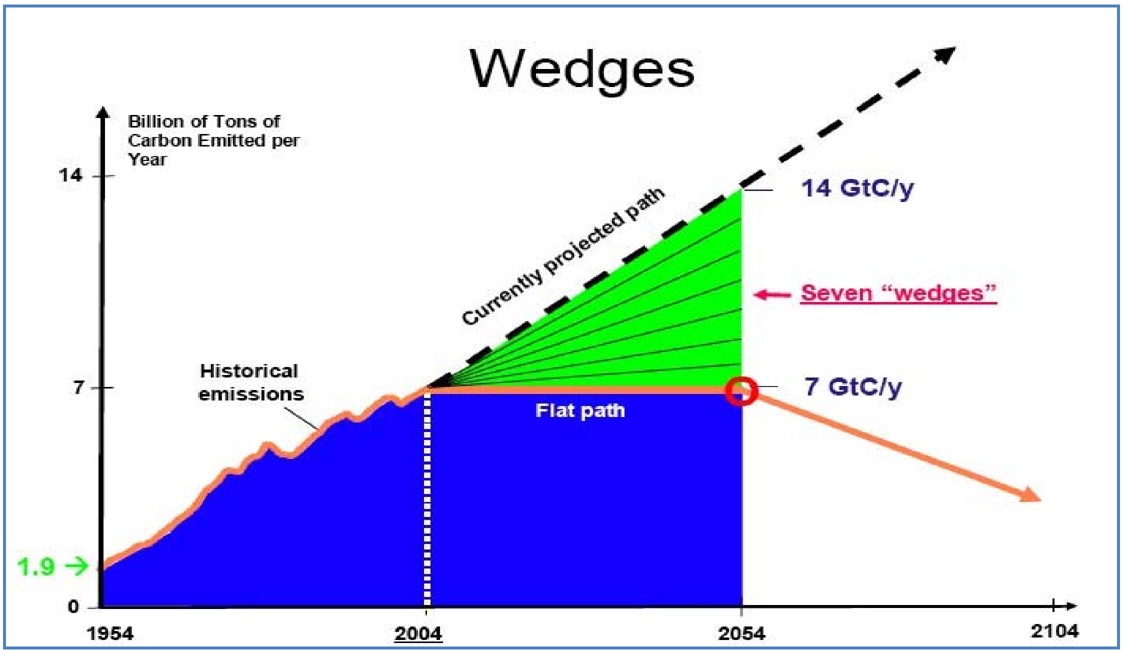

Figure 2. The '7 wedges' concept fathered by Pacala and Socolow (2004). Iron fertilisation activities could act as a wedge which could be used in association with other mitigation strategies to take the current CO_2 emissions from 14 Gt of carbon per year down to 7 Gt by the year 2054. Diagram sourced from a presentation by Cullen J. at http://www.whoi.edu/page.do?pid=14617.

Is it possible to implement iron fertilisation strategies as a "wedge" in the climate change pie if more research is done? Would the fertilisation be justifiable and effective on large scales? Could this idea have the potential to solve the world's climate problems?

The following article seeks to address whether artificial fertilisation of the Southern Ocean with iron will be an effective way to mitigate the effects of anthropogenic CO_2 emissions on global temperatures. It addresses questions such as those arisen above, and looks further into the environmental, legal and scientific implications with a focus on the Southern Ocean as a suitable location to carry out fertilisation.

The Role of Iron and the Southern Ocean

Iron is an important micronutrient utilised by a wide variety of organisms in the global ocean. It originates as aeolian dust from sources such as rivers, volcanoes and deserts and is thought to be a limiting nutrient in 30% of the worlds oceans (Watson 2001, Boyd and Doney 2003)(Figure 3).

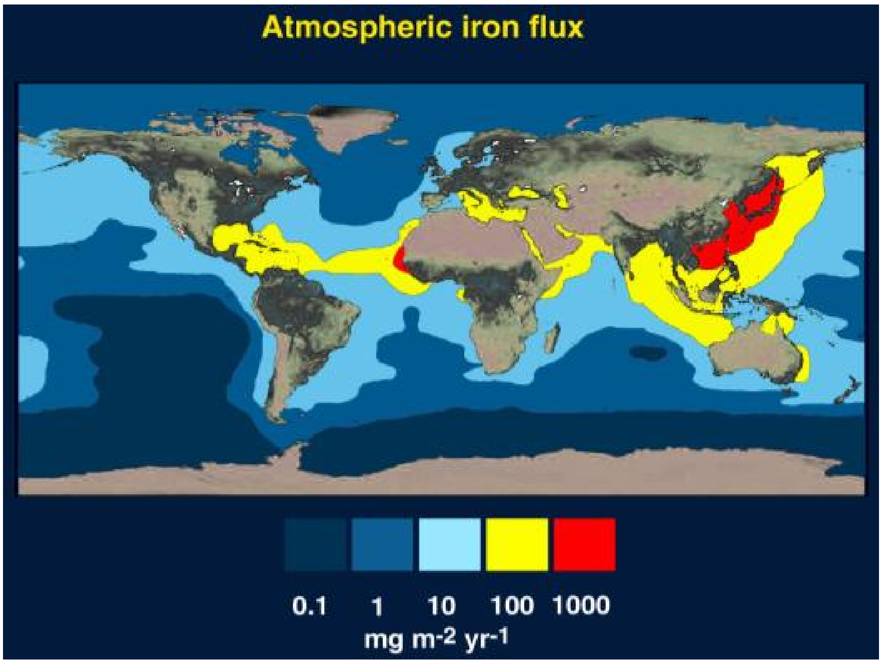

Figure 3. The atmospheric iron flux over the worlds oceans. Largest iron fluxes occur off the coasts of continents where the micronutrient is blown off fertile land. Because Antarctica is largely covered in ice, only small concentrations of iron reach the waters surrounding the continent. Diagram sourced from www.atse.org.au/uploads

For many organisms, iron is needed to efficiently undergo the basic processes needed for life such as nitrogen fixation, photosynthesis and respiration (Jickells et al. 2005). Consequently, in many marine systems where iron is lacking, levels of phytoplankton growth are low. This results in low levels of photosynthetic activity and inherently, low rates of CO_2 drawdown from the atmosphere. The process of CO_2 transport from surface waters to benthic sediments is termed the 'Biological Carbon Pump' (BCP). Therefore, an area with low levels of CO_2 drawdown can be said to have a relatively inactive BCP.

Ice core records taken from Antarctica with the intent of solving the puzzle of past climate conditions have yielded that there is a clear correlation between temperature, atmospheric carbon levels and dust levels (Figure 4). 'During past glacial periods, naturally occurring iron fertilisation has repeatedly drawn down as much as 60 billion tons of carbon out of the atmosphere' (Powell 2008).

There is also evidence that in the past, iron may not have always been a limiting factor for phytoplankton growth. During the evolution of the first prokaryotes, oceans were not as oxygenated and iron was only required in vanishingly small quantities. In today's oceans, phytoplankton require iron supplementary to that delivered to the surface by upwelling (Jickells et al, 2005).

The role of natural sources of iron in carbon sequestration is important, as scientists can learn much from this natural process. Analysis of natural processes can assist scientists in establishing whether the most effective iron sources come from the atmosphere, the melting of icebergs or upwelling (Powell 2008). A study carried out in the Kerguelen Islands on the effect of natural iron sources on carbon sequestration yielded that upwelling of natural iron sources was not only very effective at drawing down CO_2 (Pollard et al. 2005), but that this natural fertilisation was '10 to 100 times more effective at removing carbon from surface waters than any other artificial experiment has been' (Powell 2008). This is thought to be because this naturally occurring iron is much more usable than inorganic iron used in artificial studies, due to the binding of the natural iron to molecules in the seawater (Powell 2008).

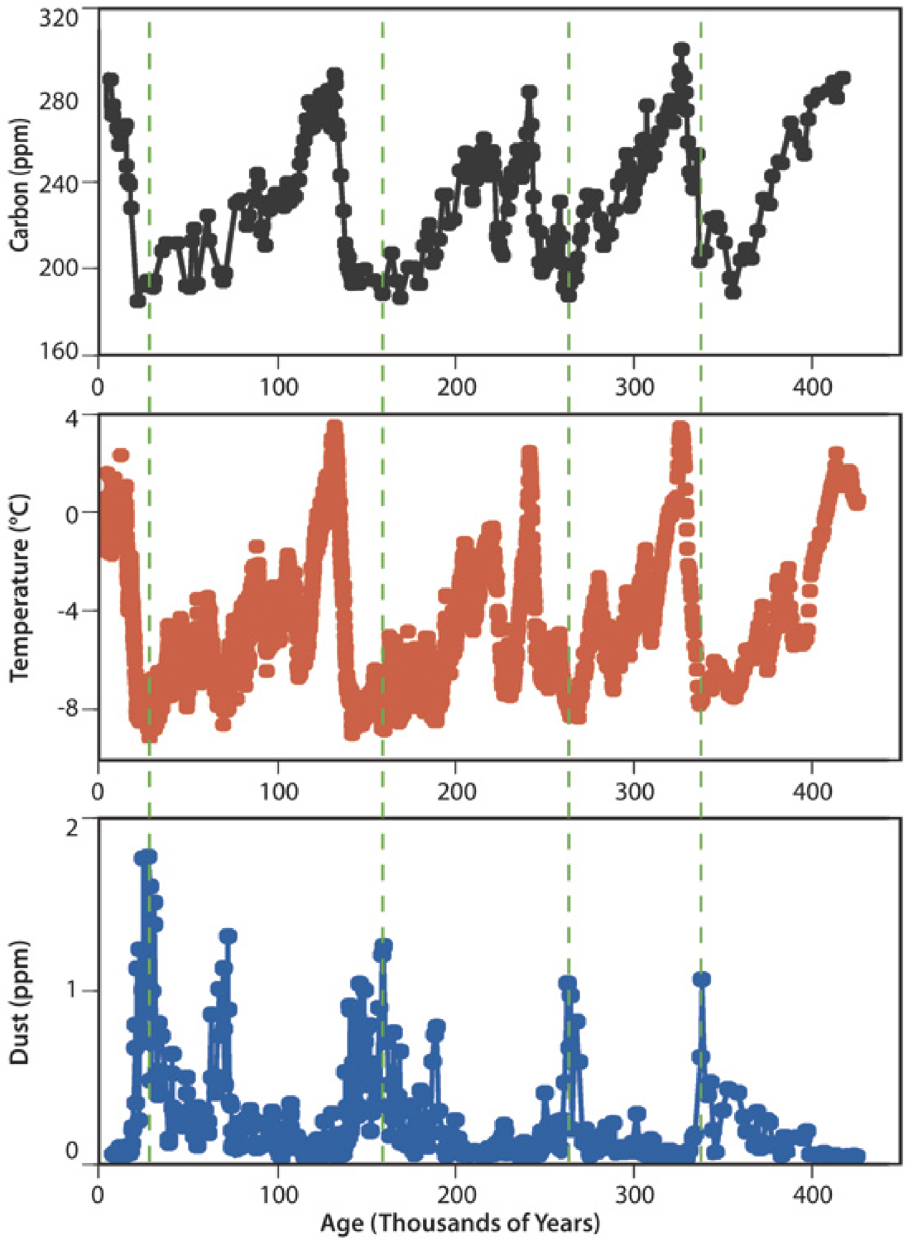

Figure 4. Information gathered from Vostok Station ice cores, illustrating the relationship between atmospheric carbon dioxide, air temperature and dust. When carbon dioxide levels and temperature are low, levels of iron-containing dust are high. Diagram sourced from www.whoi.edu/oceanus/viewImage.

The areas of ocean which are the most responsive to and most lacking in iron are termed 'High Nutrient Low Chlorophyll' (HNLC) areas. These areas are characterised by large concentrations of nutrients such as nitrate, silicate and phosphorous which would usually result in high primary productivity and high chlorophyll levels detected in the surface waters, but unusually low amounts of phytoplankton are found. Iron is the nutrient which is probably needed for increased growth, although scientists acknowledge that a large number of factors interplay such as light and grazing effects (Jickells et al. 2005).

The Southern Ocean is one such HNLC area, and represents 20% of the world's ocean (Bathmann et al.2000) (Figure 5). It acts as both a source and sink for CO_2, varying within different study areas where the most active pumping of CO_2 through the water column occurs in the summer months when light availability is high (Tréguer and Jacques 1992, Robertson and Watson 1995). Being the largest HNLC region on the world, the Southern Ocean has the greatest potential to sequester CO_2 if its iron supply is supplemented (assuming iron limitation is the reason for low levels of productivity). Dust is supplied to the Southern Ocean from small continents and deserts such as Australia, Argentina and South Africa (Jickells et al. 2005). If dust levels in these regions are altered significantly for any reason, this could lead to huge alterations in the productivity of the Southern Ocean.

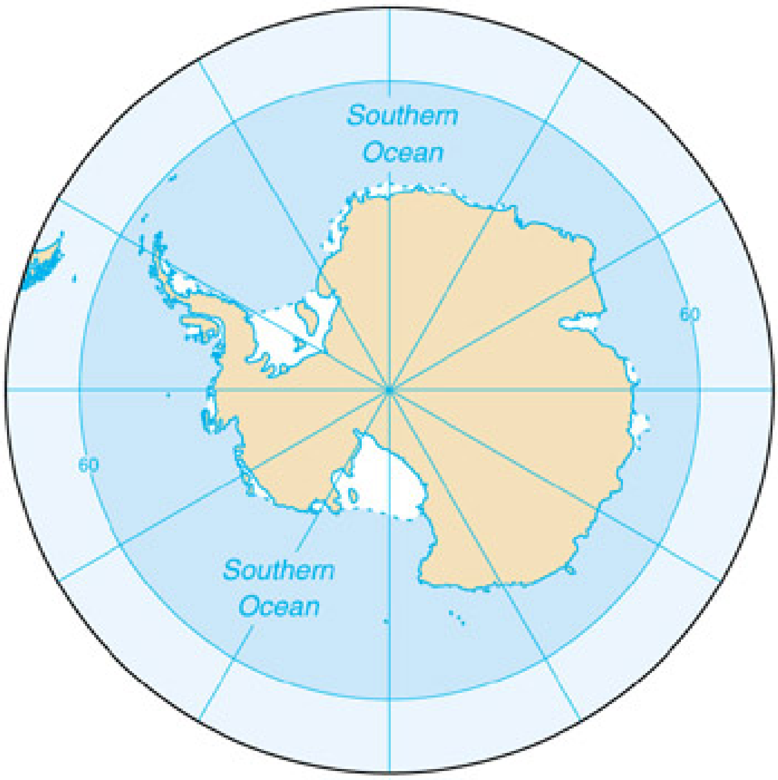

Figure 5. Schematic diagram delineating the area of the Southern Ocean south of 60°S. Diagram sourced from http://www.ecophotoexplorers.com/images/antarctica/southern_ocean_map.jpg.

Jickells (2005) notes that the altering of terrestrial ecosystems which has been suggested in order to make them more efficient carbon sinks, may cause less dust to travel over the ocean, causing less active biological carbon pumping in the marine system and cancelling out any alteration of the terrestrial system.

It can be established from the above discussion that the Southern Ocean is a very suitable location to carry out iron fertilisation experiments providing that the above assumptions on iron limitation are correct. According to a study by Tilbrook et al. (1995), the Southern Ocean already accounts for approximately 10-20% of the total world ocean CO_2 drawdown, removing up to 0.4 Gt of carbon per year from the atmosphere.

To date, only 12 iron fertilisation projects have been able to demonstrate that CO_2 sequestration occurred during the study (Figure 6). Alarmingly, the sequestration levels measured were much smaller than expected, where approximately 1000 tons of carbon were sequestered as opposed to the 30,000 to 110,000 expected. These predicted numbers were based on results from laboratory experiments (Boyd et al. 2007). Of the 12 of these experiments, 6 were conducted in the Southern Ocean. A brief outline of five of these experiments is provided below (information on the 6^{th} SAGE experiment is sparse and not published at present).

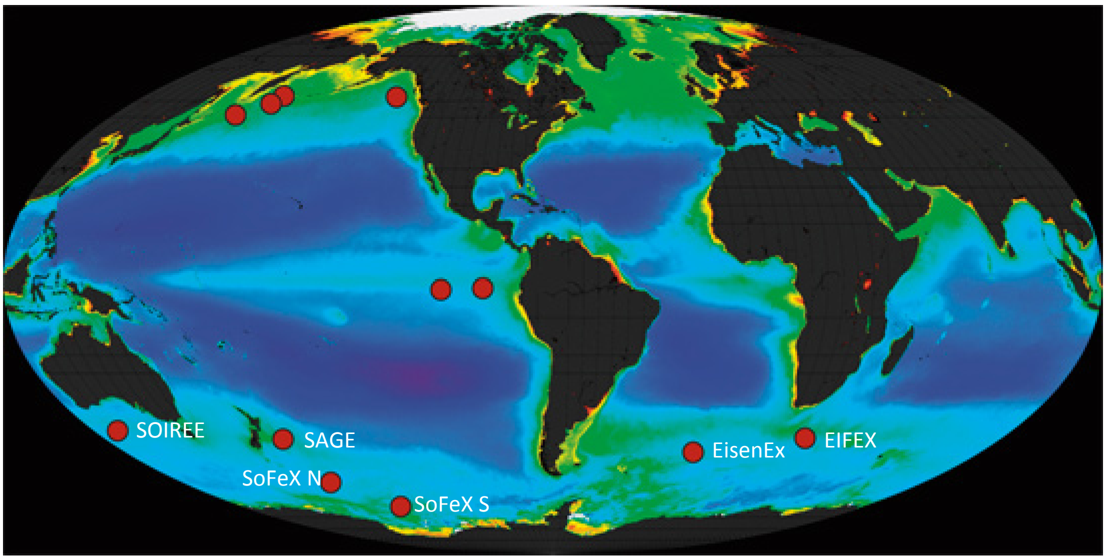

Figure 6. Locations of the 12 iron fertilisation experiments that have demonstrated some CO_2 drawdown during the study period. The 6 fertilisation experiments occurring in the Southern Ocean are located at the base of the map. Diagram modified from http://www.whoi.edu/oceanus/viewImage.do?id=57448&aid=34167

1999: The Southern Ocean Iron Release Experiment (SOIREE)

'SOIREE' was the first large-scale iron fertilisation experiment in the Southern Ocean. Scientists used the fluorescent tracer chemical sulfur hexafluoride (SF_6) to measure chlorophyll and nutrient concentrations in the water following Fe fertilisation of 64km^2 patches of ocean. A total of 1750kg of iron was added during the 14 day project undertaken during summer (Boyd and Law 2001).The bloom that resulted remained on the ocean surface for 13 days (Figure 7), and the dominant phytoplankton found were diatoms such as *Fragilariopsis kerguelensis*. It moved 40 nautical miles east and expanded to 50km^2 in size.

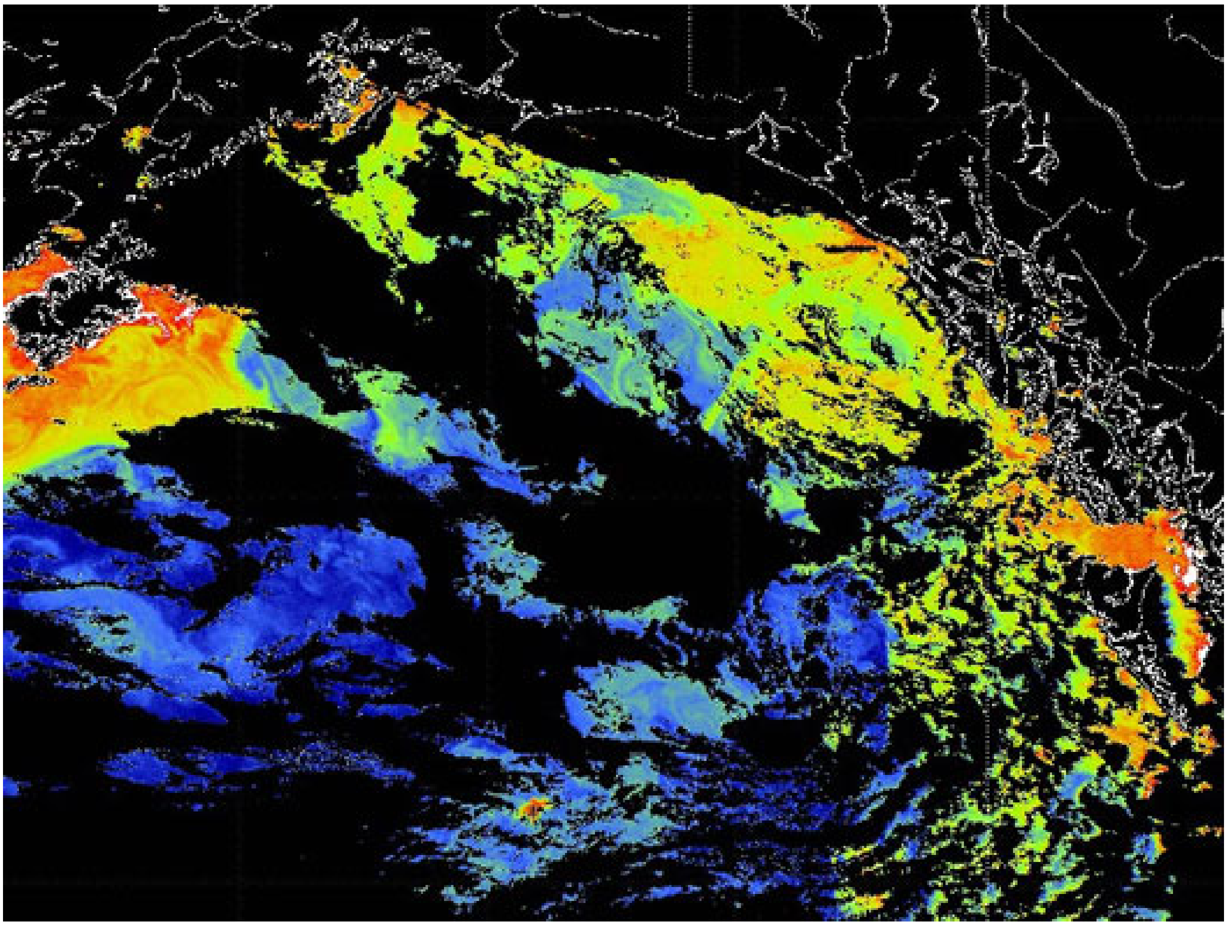

Figure 7. Satellite photograph of the SOIREE study area. The bloom resulting from the artificial iron fertilisation carried out in the study can be seen at the bottom of the image in the centre. Warm colours such as red, orange and yellow indicate high levels of chlorophyll α. Diagram sourced from http://daac.gsfc.nasa.gov/oceancolor/images/SERIES_iron_patch_halfsize.jpeg

The experiment yielded that increased primary productivity occurred after fertilisation and ocean surface CO_2 concentrations decreased, but results regarding stimulation of the Biological Carbon Pump (BCP) were inconclusive with relatively little sinking of phytoplankton to sediments. Forty days after the experiment had ceased, remnants of the bloom were still present in surface waters (Boyd and Law 2001). No significant change in mesozooplankton stocks was recorded, relative to surrounding waters that were not fertilised (Boyd et al. 2007).

2000: EisenEx Iron Experiment

EisenEx was a 22 day experiment carried out in an eddy characterised by strong winds and a highly dynamic oceanographic system, located at 48°S latitude (Bakker et al. 2005). Like SOIREE, a SF_6 tracer was used to distinguish fertilised and unfertilised patches from one another, and to act as a proxy for the additional iron (Bakker et al. 2005). A total of 2350kg of iron was added over the study which was carried out in November. This experiment yielded similar results to SOIREE in terms of species composition, where diatoms were the dominant phytoplankton and mesozooplankton stocks remained constant (Boyd et al. 2007). Interestingly, the EisenEx experiment drew down four times more CO_2 than SOIREE, which can probably be attributed to the strong winds at the location where EisenEx was carried out, and increased mixing of the water column. It was decided that the EisenEx site may have a greater potential to sequester CO_2 due to the current system found there which facilitates transport of carbon to the deep ocean (Bakker et al. 2005).

2001/2002: Southern Ocean Iron Fertilisation Experiments (SoFeX)

Two SoFeX experiments were carried out in two different years at two seperate sites. The first was a southern site with high concentrations of both nitrate and silica in the surface waters. The second was a more northern site high in nitrate and low in silica. Iron addition resulted in significant algal growth at both sites, with the most growth occurring at the southern site. This highlights the important role of silica. Both experiments were carried out in summer and slightly more (1700kg) of iron was added to the ocean at the northern site as opposed to 1300kg at the southern site. The resulting bloom at the southern site was largely comprised of diatoms, whereas a mixed composition of phytoplankton resulted at the warmer northern site. Mesozooplankton stocks did not significantly differ to background stocks at both sites (Boyd et al. 2007). Scientists used sediment traps to record sinking rates of phytoplankton following fertilisation. Although some sinking was recorded to 500m at both sites, relatively no phytoplankton sunk to over 1kilometre depths suggesting that the BCP was not stimulated and that sequestered CO_2 may easily be released back into the atmosphere (Coale et al. 2004, Buesseler and Boyd 2003). Furthermore, it was estimated that it would take 1 million SoFeX experiments covering 1 billion km^2 to draw down only 30% of annual anthropogenic emissions (Buesseler et al. 2004).

2004: European Iron Fertilisation Experiment (EIFEX)

EIFEX was conducted in late summer to early autumn in an eddy located in the Antarctic Circumpolar Current, similar to the one in which EisenEx was carried out (Cavagna et al. 2007).2840kg of iron was added to the surface waters over the 37 days of the study– the largest quantity of iron added in any of the 12 successful experiments to date (Boyd et al. 2007). The results from this experiment differed to previous experiments in that phytoplankton, with the exception of photosynthetic dinoflagellates, decreased during the experiment subsequent to iron addition (Peeken 2006). Again, diatoms were the dominant algae and an increase in mesozooplankton was observed (Boyd et al. 2007).An increase in the export of carbon was also recorded (Boyd et al. 2007), indicating that the disappearance of phytoplankton as the experiment progressed may be due to increased sinking rates or intensified grazing by zooplankton. The experiment recorded that carbon sequestration occurred as far down as the seafloor (Powell 2008).

Summary of Southern Ocean Experiments to Date

No harmful effects to the marine environment have been detected as a result of any of the above experiments, according to Powell (2008). All of the experiments used similar methods to ensure that they had comparative value, and involved the release of dissolved iron sulfate into the surface waters and mapping of the bloom using ship borne instruments. Blooms were found to travel over 1000km in some cases, and extended to depths of 100m (Powell 2008). The SF_6 tracer used in the majority of the experiments to detect bloom movement is itself a greenhouse gas, where 'one kilogram added in an experiment is equivalent to releasing 7 tons of carbon dioxide...but this amount is insignificant compared with the amount of CO2 drawn down by the bloom' (Powell 2008).

The experiments above did not look at any detail into the amount of export that resulted from fertilisation. This aspect of the studies is perhaps the most important as it will indicate just how successful the blooms are at stimulating the BCP. Studies have usually been constrained by time and money, where ships are not able to conduct the experiment long enough to assess the fate of the artificial blooms (Powell 2008). Most of the export in the above experiments was only recorded to a maximum of 500 metres. Carbon reaching this depth only has the potential to be sequestered for time scales in the order of decades, and this would only be of use in biding scientists more time to come up with more efficient methods. It appears that there is much room for continued experiments, although it must be acknowledged that these past studies were done on relatively small scales and that mesoscale experiments proposed for the future could have vastly different outcomes.

Jorge Sarmiento, a speaker at the 2007 Woods Hole Oceanographic Institution Symposium on Iron Fertilization made some important remarks about the Southern Ocean and its role in carbon sequestration. He highlighted the huge potential for the Southern Ocean to sequester larger amounts of CO_2 due to the high levels of nutrients waiting to be used up by the phytoplankton. The last vital part of the recipe is iron and once added, will start a chain of events which will set the BCP into motion. Sarmiento also highlighted problems that may arise such as the pack ice as a significant obstacle and the 24 hour darkness which occurs in winter. The high levels of mixing which occur in the Southern Ocean due the strong winds found there may mean that any sequestered carbon is readily returned to the surface during overturning of the water column. There is also the obvious problem that conditions differ markedly over such a wide expanse of ocean, and areas that appear suitable are also the most difficult to work in (Powell 2008).

Regulation of Iron Fertilisation in the Southern Ocean

Before delving into the possible environmental impacts of iron fertilisation, it is necessary to examine whether these activities are in fact legal in the worlds oceans and in particular, the Southern Ocean. The next section builds on information collated in a review written in April 2007 on the legal situation present at that time. It discusses the legality of Southern Ocean iron fertilisation experiments were they to be carried out within the area south of 60°S. The legal regime governing the activities in this area would be the collective framework of Antarctic Treaty instruments. The provisions of these instruments are based on the ‘precautionary principle’ which suggests that activities which have the potential to cause harm to an environment should not be carried out, even if the actual effects remain unknown.

The Protocol to the Antarctic Treaty on Environmental Protection (Madrid Protocol 1991)

The provisions of the Madrid Protocol apply to the area in Article VI of the Antarctic Treaty defined as south of 60˚S latitude. According to the Protocol, activities (such as iron fertilisation) must avoid ‘significant adverse effects on air or water quality’ and ‘significant changes to the marine environment’. Scientists need to take account of an activity’s ‘scope, intensity and duration, cumulative impacts, and possible unforeseen effects of activities carried out both within and outside the Antarctic Treaty area’ (Madrid Protocol 1991, Art. 3, 2).

Environmental Impact Assessments are addressed in Annex 1 and are a vital component of the Madrid Protocol whereby activities such as scientific research are tightly regulated. The Annex states that ‘if an activity is determined as having less than a minor or transitory impact, the activity may proceed forthwith’ (Madrid Protocol 1991, Annex 1, Art. 1, 2). A loophole exists here where it is uncertain whether iron fertilisation has more than a minor transitory impact on the environment. Unfortunately, the Protocol does not delve into the meanings of 'minor' and 'transitory', making it relatively impossible to distinguish if an activity falls into these categories. By using literal meanings, it can be established that an activity that has a 'minor transitory' impact would be a 'lesser activity which does not last long'. This statement is redundant in terms of iron fertilisation, as it gives no indication of what 'long' is in terms of an experiment's duration. Practically any state planning to conduct an iron fertilisation experiment can therefore argue that their experiment is likely to have only a minor transitory impact regardless of its scale (Ericson 2007).

Under Annex II of the Protocol (Conservation of Antarctic Flora and Fauna), iron fertilisation experiments would be classed under 'harmful interference' and therefore prohibited where they result in 'significant adverse modification of habitats of any species or population of native mammal, bird, plant or invertebrate' (Madrid Protocol, Annex II, Art. 1h). Of specific relevance is Article 4, which prohibits the introduction of any alien organisms into the water in the Antarctic Treaty area. Introduction of such organisms may be an indirect effect of fertilisation when there is significant alteration of water quality following addition of iron.

Annex IV addresses the issue of marine pollution. Pollution can be defined as 'the contamination of air, water or soil by substances that are harmful to living organisms'[1]. It is thought that large quantities of iron can be harmful to organisms not only by altering food web structure as mentioned above, but phytoplankton blooms reduce oxygen levels in the water, creating hypoxic conditions in localised areas (Jones 2001). It can be argued that iron fertilisation is marine pollution and is therefore prohibited as it involves 'discharge into the sea of any substance in concentrations that are harmful to the marine environment' (Madrid Protocol 1991, Annex IV, Art. 4). Furthermore, the Protocol states that 'due consideration shall be given to the need to avoid detrimental effects on dependent and associated ecosystems outside the Antarctic Treaty area' (Madrid Protocol 1991, Annex IV, Art. 8). This implies that states carrying out iron fertilisation activities north of the Convergence have an obligation to consider ecological impacts and avoid irreversible environmental harm when planning experiments (Ericson 2007).

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[1] **pollution. (n.d.). *The American Heritage® Science Dictionary*.**
http://dictionary.reference.com/browse/pollution

The Convention for the Conservation of Antarctic Marine Living Resources 1980 (CCAMLR)

Scott (2005) notes that CCAMLR is likely to be an ineffective tool for regulating iron fertilisation as this instrument is concerned only with activities that involve harvesting. An increase in fish populations can be an indirect consequence of iron fertilisation where some experiments are designed for this purpose, such as one planned to increase fish stocks in the Gulf Stream (Scheuller 1999). Iron experiments designed to mitigate climate change are unlikely to have this in mind and because an increase in fish stocks is merely an indirect consequence of fertilisation, scientists are unlikely to be held accountable by any provisions in CCAMLR. Attention must however be drawn to the text in Article 2(3) which states that 'any harvesting and associated activities in the area to which this Convention applies shall be conducted within the provisions of this Convention'. It can be argued from this statement that because iron fertilisation can result in a rise in fish numbers it is an "associated activity".

The Antarctic Treaty (1959)

Although the Antarctic Treaty is primarily concerned with territorial sovereignty issues on the continent, it is a useful tool for examining the underlying purpose of Antarctic legal instruments to maintain Antarctica as a peaceful continent characterised by freedom of scientific investigation (Ericson 2007). Article VI of the Antarctic Treaty 1959 is perhaps the most important component of the Antarctic Treaty System when it comes to iron fertilisation, as it is this article that prevents Antarctic legal instruments from having any real jurisdiction. Article VI states that 'the provisions of the Treaty shall apply to the area south of 60˚ South Latitude...but nothing in the present Treaty shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law with regard to the high seas within that area.'

The United Nations Law of the Sea Convention (UNCLOS) describes the 'high seas' as being 'all parts of the sea that are not included in the exclusive economic zone, in the territorial sea or in the internal waters of a State'(UNCLOS pt. VII, Art. 86). Under UNCLOS, states are permitted to undergo any marine scientific research in the high seas – beyond the exclusive economic zone as long as it is consistent with the provisions of the convention, i.e. it does not involve 'dumping' or 'marine pollution' (Ericson 2007).

The London Convention Meeting on the Regulation of CO_2 Sequestration

The London Convention, also known as the Convention on Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol 1996) was enacted in an attempt to control the dumping of waste into the ocean. It is not part of the Antarctic Treaty System but is relevant nonetheless. In June 2007, the scientific group of the London Convention addressed the concept of iron fertilisation and its future regulation. During the meeting it was noted that Annex I of the London Protocol (1996) had recently been amended to allow carbon sequestration in geological formations. Participants mentioned the IPCC 2007 report which stated that ‘geo-engineering options, such as ocean fertilisation to remove CO_2 directly from the atmosphere...remain largely speculative and unproven, and with the risk of unknown side-effects’ (World Conservation Union 2007, IPPC 2007 p.20). This statement was the underlying theme of the meeting where it was reiterated frequently that there is no current system put into place to prevent these experiments from ‘creating hazards to human health, harming living resources and marine life, damaging amenities or interfering with other legitimate uses of the sea’ (World Conservation Union 2007).

The meeting addressed controversial issues such as the responsibility for environmental damages resulting from iron fertilisation, the role of states in preserving the high seas and the overarching question on who is qualified to make decisions on whether mesoscale experiments can be classed as pollution. It became evident that further research needs to be carried out and scientists were invited to ‘bring to the attention of the Parties to the London Convention and Protocol the urgent need for legal studies to determine what further action, if any, is necessary to bring ocean fertilisation projects under appropriate scrutiny and control’ (World Conservation Union 2007). The resulting conclusion was therefore that the future rests on the shoulders of scientists, and unless the likely effects of large scale fertilisation can be demonstrated, the legal status of the issue is likely to remain static.

Environmental Consequences of Mesoscale Iron Fertilisation

The most controversial side to the iron fertilisation debate is the environmental effects that mesoscale experiments may have. The possible effects suggested by scientists and policymakers are varied and include the significant alteration of food webs in the vicinity of the algal blooms. Hall and Safi (2001) acknowledge that the ‘microbial food component of the food web is important in the HNLC regions of the Southern Ocean’.

During the SOIREE experiment, changes to community structure were monitored in detail, and it was found that changes did occur but that they did not have a marked effect on the way the community was functioning (Hall and Safi 2001).Bacterial production tripled, but the numbers of bacteria remained fairly constant. Populations of picophytonplankton increased markedly during the first week of the experiment, but decreased to base levels shortly afterwards (Hall and Safi 2001). This may be due to intra-specific competition which regulated the numbers in the population or increased grazing by zooplankton. Nanophytoflagellate numbers increased six-fold which enhanced the rate of carbon flow through the food web. Microzooplankton abundance increased, probably as a result of the increased carbon flow occurring in the water column. It appears that grazing by the zooplankton kept algal numbers in check, increasing the amount of recycling and regeneration in surface waters – an undesirable effect as this prevents the carbon from reaching the sediments. Hall and Safi (2001) conclude that 'the addition of Fe to a 250km^2 patch of the Southern Ocean in late summer had a considerable impact on all components of the microbial food web,...the lack of significant increases biomass...with the exception of the nanophytoflagellates suggests that tight coupling between prey and predators was maintained throughout the experiment'.

Although these results seem promising, it is important to note the small size of the experiment and the concerns raised by other scientists. Powell (2008) notes, 'the desired effects – drawing down carbon dioxide from the atmosphere and sequestering carbon in the deep sea – are only two of the possible consequences... assemble a list of ways iron fertilisation may harm the ocean...and it quickly becomes lengthy and distressing'.

Environmental Effects of Algal Blooms

The effects of mesoscale algal blooms have been seen in oceans all over the world. Often, the blooms have harmful effects on the marine ecosystems in pelagic and benthic waters below. In the North Sea, eutrophication of surface waters caused deoxygenation of benthic waters, causing the death of numerous fish and invertebrates in the German Bight in the 1980's and a similar event was seen in the Baltic Sea in the 1960's (Clark et al. 1997). Hypoxic conditions within the California Current system were recognised in 2002, as a result of a flow of subarctic water entering the area that was low in dissolved oxygen. This caused the mass mortality of fish and invertebrates (Grantham et al. 2004). There are concerns that the use of large quantities of nutrients by organisms in the vicinity of artificially fertilised blooms will cause nutrient depletion and decreases in oxygen in localised areas, and have consequences similar to those mentioned above (Powell 2008).

In some cases, the fertilisation of surface waters with limiting nutrients does not cause an expected bloom situation. This was illustrated in a study by Thingstad et al. (2005) that showed a decrease in chlorophyll with the addition of phosphorous.

The case of the Mentawai Islands in 1997 is particularly relevant, where large quantities of iron originating from wildfires in Indonesia entered the ocean offshore from Sumatra, causing a large red tide algal bloom which led to asphyxiation of the reef below, and the death of close to 100% of the coral and reef fish (Abram et al. 2003).

These studies are a stark contrast to a comment made by the Green Sea Venture Corporation that 'there is absolutely no possibility that even prolonged and large iron fertilisations would create anoxic conditions in deep waters' (Markels and Barber 2001). The effects of algal blooms on food web response vary widely over different locations and studies done in the Southern Ocean are few and far between. The possible proliferation of toxic algae species in the blooms is a very real threat as past experiments have caused increases in certain species found to be associated with harmful blooms (Powell 2008c). While toxic phytoplankton can cause harm to some species, it may have no effect on others and extrapolation of results from one set of circumstances to another may be inappropriate due to the situation-specific nature of the issue (Turner and Tester 1997).

Increasing Fish Stocks as a Consequence of Algal Blooms

Another possible outcome of algal blooms is that they may actually increase fish stocks in the vicinity of a bloom. This has been shown in various studies including a study done by Platt et al. (2003) who found that increases in larval fish abundance were correlated with timing and location of the spring algal bloom off Nova Scotia in Canada. Various proposals have been put forward by scientists to carry out fertilisation of the ocean to increase fish stocks and simultaneously draw down $CO_{2.}$

Michael Markels Jr. is an employee of a business and finance company based in the United States of America named Versar Incorporations. He is the most well known proponent of iron fertilisation at the present time and his radical ideas and claims are widely acknowledged. Markels is so successful at pushing the idea of iron fertilisation because he identifies additional problems which this fertilisation science can solve, such as the rapid depletion of fish stocks which is currently occurring in oceans around the world. This appeals not only to fisheries organisations but also to environmentalists, provided that the reasoning behind the fertilisation is feasible and the appropriate issues are addressed. It can be used to advertise the benefits of iron fertilisation to the general population as it focuses on socioeconomic benefits of the science. Markels has released numerous patents which claim that the replacement of limiting nutrients into the ocean around areas where fish stocks are low, will allow the eventual growth and recovery of the stocks found there. He purports that one such fertilising agent is iron.

Markels 1995 patent likens the ocean to a desert in which only small pockets of life abound and implies that areas with high levels of diversity can be distinguished from sparser areas simply by observing from them from a boat or plane. He proceeds to give a 'detailed' overview of areas in which fertilisation could be carried out, and applies similar facts and figures to areas of ocean which appear similar in their nature, but can not feasibly be compared due to the complex nature of the marine system. The terrestrial ecosystem is directly compared to the marine ecosystem in the following statement; 'On the land, fertilization is almost always accompanied by planting. In the ocean, the fertilization may be combined with the introduction of algae, egg masses and other organisms, including juvenile fish from hatcheries. This may further increase the production of seafood from the ocean' (Markels 1995). What about the consequences of perturbing the natural environment in such a way? Is there any real evidence to show that adding a combination of these organisms would increase fish stocks? Scheirmeier (2003) states that 'the life cycle of plankton and the evolutionary trends it has followed are completely different from those of terrestrial organisms'. Markels' statements assume that the marine environment is a highly predictable entity. Any scientist, whether a novice or an expert, is aware that it is not.

It is not necessary to delve further into the details of this patent, as it is clear that the document is based on a limited understanding of the processes involved and is alarming in its simplicity. Only once does Markels address any environmental impacts such large scale fertilisation (250,000 tons of fertiliser spread over 140,000 km^2) could cause when he says 'the fertilizer must not contain any toxic chemicals in a concentration that would harm the sea life, and must be free of pathogens that could be ingested by the consumers of the seafood' (Markels 1995). This statement is all very well in theory, but it is the indirect and unintentional impacts of such fertilisation activities that are the most worrying, and they are not mentioned anywhere in the patent.

Once such indirect effect brought to light is the possibility that iron fertilisation may increase the production of other greenhouse gases that may be released, counteracting the effect of CO_2 sequestration (Boyd et al. 2007). Such gases include nitrous oxide and methane which are the products of decomposition occurring at the benthos (Powell 2008). It has also been found that phytoplankton can release dimethylsulfide into the atmosphere which creates cloud-forming water droplets that can assist in cooling the climate (Powell 2008). This could be an advantageous side effect of iron fertilisation and will no doubt be the focus of future studies.

Like Michael Markels, proponents of iron fertilisation such as the companies Climos (www.climos.com) and Planktos (www.planktos.com), make the error of comparing terrestrial and marine ecosystems with each other in order to justify the experiments. Even if mesoscale experiments in the future do result in minor transitory impacts on the Southern ocean system, it is naive and ignorant to compare such completely different ecosystems. Comments on the Planktos website such as ‘we can expect any detrimental environmental consequences to be far less dramatic than similar programs imposed on terrestrial systems’ and ‘it's clear that the ocean environment is the place where we can do the most while interacting and impacting on the environment the least’ are completely unfounded.

The uncertainty surrounding the effects of iron fertilisation on marine ecosystems is illustrated below.

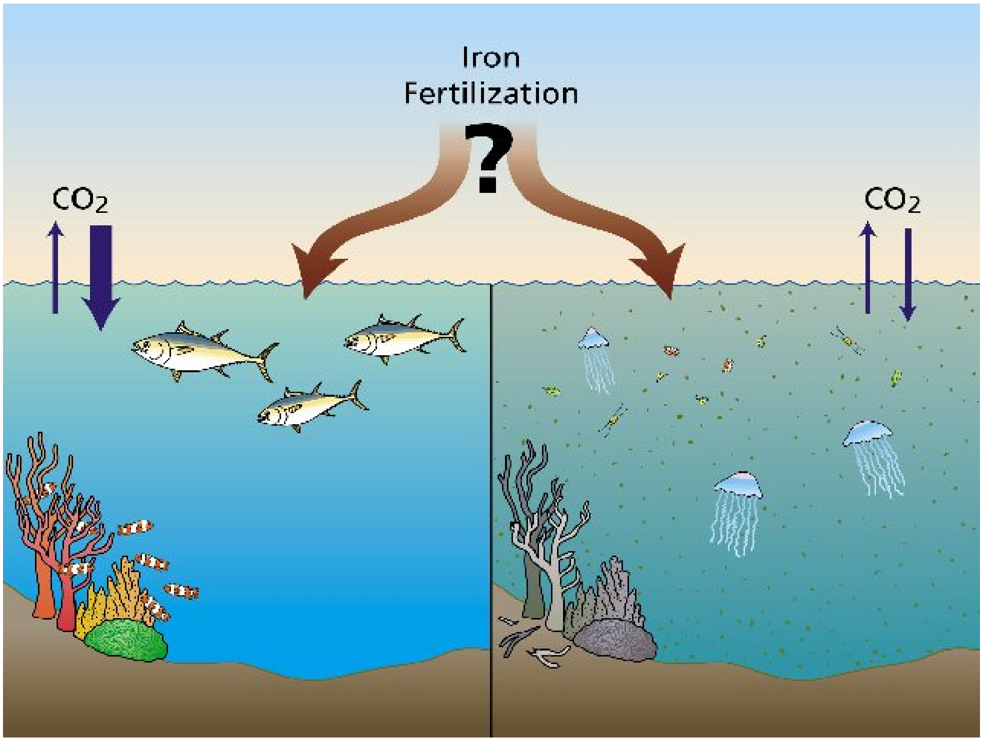

Figure 8. Iron fertilisation in HNLC regions such as the Southern Ocean could have a variety of different effects on the food web. The scenario on the left of the image illustrates the outcome which proponents of iron fertilisation predict – increased drawdown of CO_2 and an increase in fish stocks. The scenario on the right hand side of the image illustrates the outcome which opponents of iron fertilisation warn might happen – no net increase of carbon dioxide sequestration, and anoxic conditions in the water column which cannot sustain life.

Alternative Eco-Engineering Schemes

Judging by the above evidence which does not favour mesoscale injection of iron into the Southern Ocean, it is necessary to take a brief look at the proposals for other sequestration methods that could be used as an alternative. If either of the following methods are proven to be worthwhile, iron fertilisation may cease to go ahead if it is found to be less profitable or less efficient.

Installing Pipes into the Ocean to Aid Carbon Sequestration

An article in an edition of Nature in 2007 proposes that thousands of pipes approximately 100 – 200m long and 10m in diameter could be used to pump nutrient-rich water up from the benthos into the surface waters, in order to increase primary productivity and stimulate the biological carbon pump (Figure 9). The article uses many anthropocentric phrases such as 'we propose a way to stimulate the earth's capacity to cure itself, as an emergency treatment for the pathology of global warming' in order to increase the appeal of the idea to readers (Lovelock and Rapley 2007). There are many flaws associated with this proposal, including the fact that water transported to the surface through the pipes may be rich in carbon which has already been sequestered, and this would be quickly returned to the atmosphere (Madin and Nevala 2008). It is uncertain whether this transfer of nutrients would actually stimulate phytoplankton growth and what environmental effects it may have on other parts of the food web. Many areas of the Southern Ocean are not lacking in most nutrients apart from iron, so the injection of nutrients such as nitrogen and phosphorous into surface waters may not have any significant difference on carbon sequestration.

The Salp Hypothesis

A company called 'Atmocean Inc.' has proposed an idea similar to the one above which also involves promoting the growth of salps. Salps are an important component of the zooplankton in the Southern Ocean. They graze on phytoplankton and their faecal pellets sink rapidly due to their weight, transferring carbon obtained from the phytoplankton to deep waters. The company suggests the installation of thousands of tubes into the ocean which would pump nutrients to the surface, mimicking the idea postulated by Lovelock and Rapley. The aim would be to increase phytoplankton abundance, which would in theory increase the abundance of salps. This idea also has many flaws, as the behaviour and growth of salps is not predictable, and the creation of a phytoplankton bloom does not necessarily equate to a significant increase in salp numbers (Madin and Nevada 2008).

Other projects such as nitrogen fertilisation have been proposed, but this does not apply to areas such as the Southern Ocean which is not lacking in nitrogen in most areas.

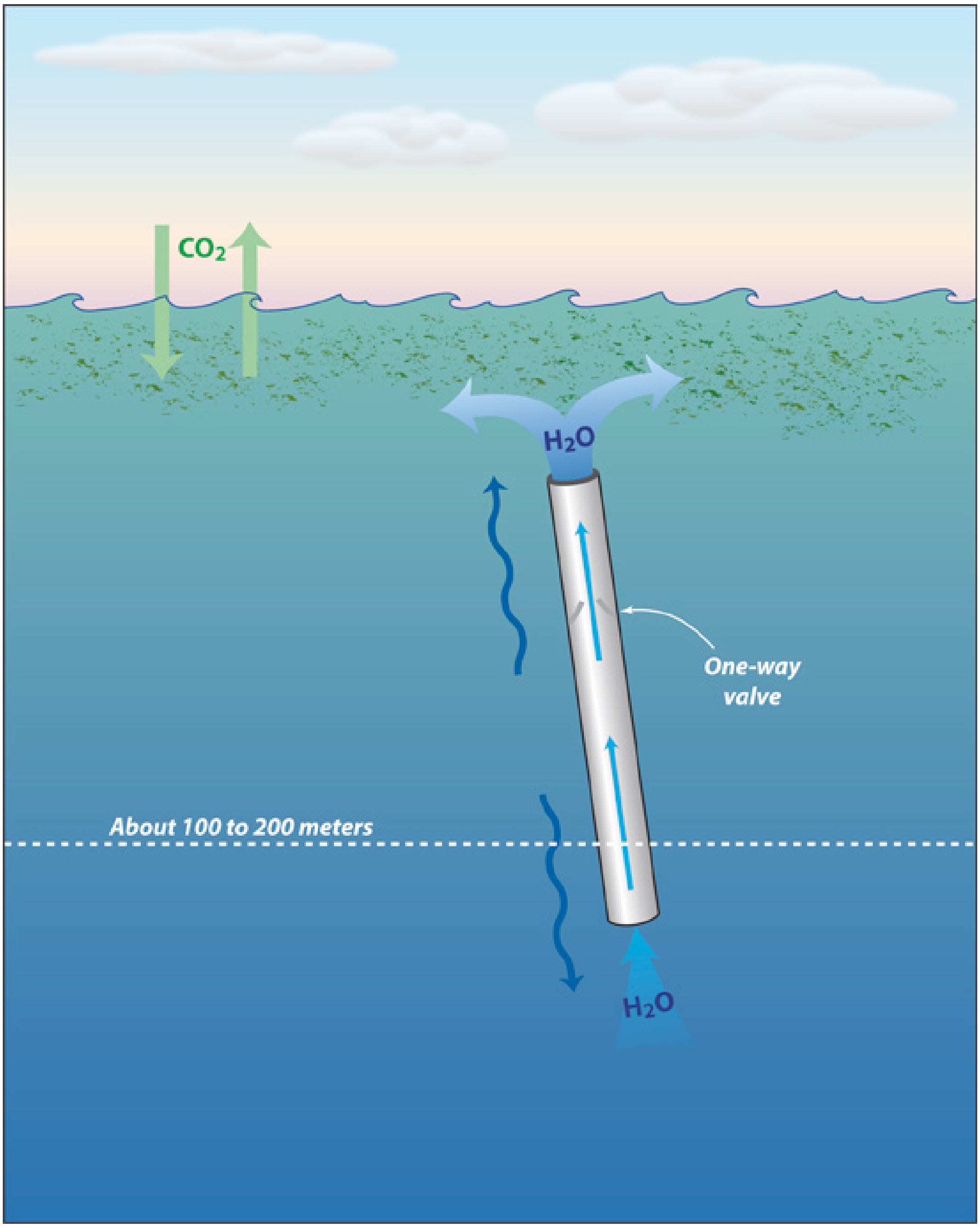

Figure 9. A schematic diagram illustrating the proposal by James Lovelock and Chris Rapley to install large pipes into the ocean which will aid in transporting nutrients to the surface waters, resulting in blooms of phytoplankton and increased CO_2 sequestration. Diagram sourced from http://www.whoi.edu/oceanus/viewImage.do?id=59909&aid=35866

The Future of Iron Fertilisation Studies in the Southern Ocean

I have chosen to write this concluding section in the first person as although this is not the usual format for such reports, I feel that it is appropriate in this case. Much of this report has focused on the potentially negative consequences that iron fertilisation may have. It has highlighted the fact that mesoscale experiments may continue to go ahead in the Southern Ocean in the future with limited or no regulation by the Antarctic Treaty instruments. I would like to bring to light some suggestions for the future development of this science. John Cullen, an oceanographer who attended the Woods Hole Institution Iron Fertilization Symposium in 2007 stated that the effects of large scale fertilisation are likely to be the fundamental alteration of biogeochemical cycles and marine systems. He purported that these effects cannot be quantified with acceptable accuracy, therefore any further experiments should not go ahead. During the same conference it was observed that 'this (iron fertilisation) is an incremental thing. If you start to see that it's going wrong, then you can roll back. Taking the first step does not inevitably mean that you have to go the whole road' (Powell 2008). The reality is, further experiments will almost certainly go ahead with or without regulation and time is running out to come up with enough evidence to prevent or perfect them.

I believe that any future experiments will be focused in the Southern Ocean and that they should be scaled up slowly in an incremental fashion, as suggested above. This would be the most environmentally friendly approach besides halting the experiments altogether. By slowly increasing the size of experiments over long time scales, we have a better chance of monitoring any resulting effects.

The Role of Ice in the Iron Fertilisation Process

I have been interested to read about the role of the ice sheet in fertilisation of the Southern Ocean and the location of the algal blooms, and I believe that this may be the key to future research. In winter, the Marginal Ice Zone (MIZ) in the Antarctic accounts for 50% of the area of ocean south of the Polar Front (Bathmann et al. 2000). In summer, the ice retreats markedly. This means that the biogeochemical and biological cycles in almost half of the Southern Ocean are dominated by advance and retreat of the sea ice. During a the digging of an ice pit in a glaciology project undertaken in the Antarctic during the 2007/2008 summer, I observed a prominent dust layer located approximately 2 metres below the ice surface. This dust originated from a storm occurring in

May 2004. Assuming this dust contains traces of iron derived from natural sources, it may have had an impact on primary productivity in the Southern Ocean at the time, and furthermore, the melting of sea ice may expel quantities of this dust into the ocean, stimulating productivity in localised areas. I propose that the effects of sea ice and icebergs on natural fertilisation of the oceans should be a focus for future research. In particular, models on the effects of climate warming on large scale ice melt could incorporate the effects of dust expulsion into them. Despite the fact that such a process may have only a small-scale effect on productivity, it would be useful to extrapolate how the ocean responds to this interaction with the ice in order to build on our current knowledge of iron fertilisation.

On investigation into this topic, it was discovered that a handful of experiments have already been undertaken on the composition of organisms found adjacent to icebergs in the Southern Ocean. One such study undertaken by Smith et al. (2007) yielded promising results. It was carried out due to the hypothesis that icebergs can exist as 'hotspots' for biological activity. It was found that numbers of krill, seabirds and phytoplankton were significantly elevated within a distance of approximately 3.7km from two drifting icebergs. Scientists estimated that the icebergs had an effect on a substantial area of surrounding water, but the magnitude of this influence needs to be addressed in future studies. It was concluded that the icebergs may have a very significant impact on pelagic ecosystems due to the nutrients released during melt, and that increased carbon sequestration may occur in areas adjacent to icebergs. I propose that specific research is needed in order to establish whether iron is the reason for this increased primary productivity and diversity around icebergs. If this can be established, we can learn much from this phenomenon, as we already know from previous studies that natural iron sources have a much more successful effect at sequestering carbon than anthropogenic methods. If it is established that iron is the reason for the patterns seen, scientists can continue to investigate the composition of organisms that results from this fertilisation, and the process in which this iron is incorporated into surface waters and utilised successfully by the organisms.

Sedwick and DiTullio (1997) conducted a relevant study on the relationship between ice and ocean productivity in the Ross Sea. It was observed that the retreat of sea ice over a 17 day period correlated with an increase in primary productivity and a decrease in nitrate, phosphate and silicate in surface waters. This implied that a catalyst (possibly iron expelled from the sea ice) had enabled phytoplankton to use up the macronutrients and net growth to occur. This was confirmed when it was found that surface waters in the vicinity of the melting ice were iron-enriched (Sedwick and DiTullio 1997). Edwards and Sedwick (1996) postulate that iceberg iron sources could result in up to

4 x 10^{10} moles of carbon per year in additional primary production. These studies did not delve into the amounts of export that occurred as a result of the algal blooms, although it is thought that iron release due to seasonal sea ice melt may have a 'key role' to play in regulating these Southern Ocean productivity (Sedwick and DiTullio 1997).

Conclusions and Closing Comments

The Antarctic and Southern Ocean ecosystem is arguably the only ecosystem left relatively untouched by humans, although this looks set to change in the near future, as the human race struggles to find solutions to its growing climate change related problems. Fisheries in the Southern Ocean are being increasingly exploited and tension is growing within the Antarctic Treaty system as an array of issues are emerging which are not currently regulated by any legal regime. Iron fertilisation is therefore one issue of many, and does not appear to be a huge priority in the Southern Ocean at the present time, however there is no doubt that this concept will not disappear until it has been proven that it will not result in any economic benefits. It is money and human welfare that are frequently the top priorities in an anthropogenically dominated world, and the environment that we rely on to survive often takes the backseat. It is likely that iron fertilisation may only be a small portion of an answer to a much larger problem and that it may cause more harm to the oceans than good to human society. It remains a 'misunderstood, oversold , and oversensationalised process that has been occurring naturally for millions of years' (Buesseler et al. 2008).

The answer to whether further mesoscale enrichment in the Southern Ocean should go ahead lies in the hands of scientists, the voices of lawyers and the pockets of economists and policymakers. Hopefully a happy medium can be reached whereby carbon can be efficiently sequestered into the Southern Ocean without irreversible perturbation to the fragile and important Antarctic ecosystem.

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