RISK ASSESSMENT FOR LOHAFEX

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0. INTRODUCTION

At its ninth meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD) in Bonn, Germany, in May 2008, the Conference of the Parties,
…

3. Recognises the current absence of reliable data covering all relevant aspects of ocean fertilisation, without which there is an inadequate basis on which to assess their potential risks;

4. Bearing in mind the ongoing scientific and legal analysis occurring under the auspices of the London Convention (1972) and the 1996 London Protocol, requests Parties and urges other Governments, in accordance with the precautionary approach, to ensure that ocean fertilisation activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities; with the exception of small scale scientific research studies within coastal waters. Such studies should only be authorised if justified by the need to gather specific scientific data, and should also be subject to a thorough prior assessment of the potential impacts of the research studies on the marine environment, and be strictly controlled, and not used for generating and selling carbon offsets or any other commercial purposes ... (CBD Decision IX/16) (s. Annex 5).

The Contracting Parties to the London Convention and the Contracting Parties to the London Protocol have passed the resolution LC-LP.1(2008) on the regulation of ocean fertilisation at their meeting in London, October 2008
The Meeting,

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NOTING *decision IX/16 on 30 May 2008 of the 9th Meeting of the Conference of the Parties to the Convention on Biological Diversity which "requests Parties and urges other Governments, in accordance with the precautionary approach, to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify suchactivities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities; with the exception of small scale scientificresearch studies within coastal waters";*

NOTING *United Nations General Assembly resolution 62/215, concerning "Oceans andthe law of the sea", adopted on 22 December 2007, which in its paragraph 98 "encourages Statesto support the further study and enhance understanding of ocean iron fertilization";*

NOTING *that a number of other international organizations are considering the issue ofocean fertilization;*

NOTING *that knowledge on the effectiveness and potential environmental impacts of ocean fertilization is currently insufficient to justify activities other than legitimate scientific research;*

1. AGREE *that the scope of the London Convention and Protocol includes ocean fertilization activities;*

2. AGREE *that for the purposes of this resolution, ocean fertilization is any activity undertaken by humans with the principal intention of stimulating primary productivity in the oceans*

3. AGREE *that in order to provide for legitimate scientific research, such research should be regarded as placement of matter for a purpose other than the mere*

disposal thereof under Article III.1(b)(ii) of the London Convention and Article 1.4.2.2 of the London Protocol;
***4. AGREE** that scientific research proposals should be assessed on a case-by-case basis using an assessment framework to be developed by the Scientific Groups under the London Convention and Protocol;*
***5. AGREE** that the aforementioned assessment framework should include, inter alia, tools for determining whether the proposed activity is contrary to the aims of the Convention and Protocol;*
***6. AGREE** that until specific guidance is available, Contracting Parties should be urged to use utmost caution and the best available guidance to evaluate the scientific research proposals to ensure protection of the marine environment consistent with the Convention and Protocol;*
***7. AGREE** that for the purposes of this resolution, legitimate scientific research should be defined as those proposals that have been assessed and found acceptable under the assessment framework;*
***8. AGREE** that, given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed. ...*
(LC-LP.1(2008)) (s. Annex 2).

The resolution of the Contracting Parties to the London Convention and the Contracting Parties to the London Protocol as well as the CBD decision and numerous other comments on this issue (e.g. IOC) have stated the need for further scientific research to assess the impact on the ecosystem and the efficacy of iron fertilisation. The Working Group Report of the Scientific Group of the London Convention/Protocol states in paragraph 2 of annex 2 to LC/SG 31/16 (s. Annex 3):
The Working Group noted the uncertainties identified here for assessing the impacts of ocean fertilization activities represent fundamental uncertainties in our understanding of ecosystem dynamics, and the role of the oceans in the global carbon cycle. Advances in both of these basic research areas are critical to understanding climate change, and should be fostered regardless of whether or not ocean fertilization activities contribute to mitigating climate change.

The aspects of the impact on the ecosystem and the efficacy of iron fertilisation are presently not well understood. The scientific iron fertilisation experiment LOHAFEX was designed and planned to address these relevant questions that have been discussed in the scientific community already for years. The experiment was jointly planned by the Alfred-Wegener-Institute for Polar and Marine Research (AWI), Germany, and the National Institute of Oceanography (NIO), India, since 2005. The above mentioned resolution were passed in October 2008 and have necessitated a formal assessment on the basis of the scientific design of the experiment.

The LOHAFEX research proposal is based on intercomparisons of thorough investigations of natural environments from various sites and conditions with the results from a number of previous iron fertilisation experiments all carried out in the Southern Ocean (SO) including coastal waters that provide the basis for the assessment of the impact of such experiments on the environment. These results have been published in leading scientific journals (Assmy et al. 2007; Blain et al. 2007; Blain et al. 2008; Blain et al. 2008; Boyd et al. 2007; Boyd et al. 2000; Buesseler et al. 2008; de Baar et al. 1995; Henjes et al. 2007; Smetacek et al. 2004; Smetacek et al. 1997; Timmermans et al. 2008; Trull et al. 2008). This scientific evaluation of previous experiments has been subject to world-wide peer review and has highlighted gaps in the knowledge that need to be addressed in future research. This need for further research is also stressed by the above-cited resolution of the London Convention and by the decision of the CBD.

The Indo-German team of scientists will study the effects of iron fertilization on the environment by comparing the results with similar measurements carried out in surrounding, unfertilized waters in great detail with state-of-the-art methods by integrated teams of biologists, chemists and physicists over a period of about 45 days. It is scheduled to start by 25 January 2009. It encompasses the processes from growth of the minute, unicellular algae to their consumers and assesses the impact on the biogeochemistry and carbon cycle. It addresses the still open question of the fate of the carbon sinking out of the surface to the deep ocean by applying newly developed methods (neutrally buoyant sediment traps, profiling cameras, transciptomics to assess the extent of programmed cell death (apoptosis) of the algae) for the first time in such experiments. A Multicorer will be used to obtain undisturbed samples of the sediment surface and the overlying “fluff”, sedimented algae from the bloom. If successful, this experiment will be the most comprehensive one carried out to date and provide information on the behaviour and impact of phytoplankton blooms induced by iron addition, whether natural or artificial (see below). In addition, LOHAFEX will provide a wealth of basic knowledge on biodiversity changes during bloom growth and demise, organism interactions within the plankton and their effects on the biogeochemistry of the Southern Ocean (SO). The data are needed to parameterize current models of the role of the Southern Ocean in the global climate system of the past, present and future.

The assessment of the LOHAFEX experiment carried out by the Alfred Wegener Institute for Polar and Marine Research (AWI) and the National Institute of Ocenography (NIO) addresses the following points.

- expected local conditions
- possible effects on the marine environment
- control measures

It is important to state that the design of the experiment only addresses scientific questions and is not designed for generating and selling carbon offsets or any other commercial purposes. The fertilisation will be carried out over a short period of time and then the development of the bloom and its demise will be observed. The spatial scale of the iron fertilisation experiment is small in respect to the surrounding environment and covers only $6*10^{-4}$% of the Antarctic Circumpolar Current (ACC) in which the experiment is located. The addition of iron to the water is small in comparison to natural iron enrichments by coastal waters or ice bergs. The chosen location is downstream from an extensive land mass – the Antarctic Peninsula or the tip of the South American Continent– but also the island of South Georgia and contains waters with coastal plankton species.

1. PROBLEM FORMULATION

The concerns commonly associated with ocean iron fertilization (OIF) apply only to large-scale, long-term iron additions in the same site that could possibly lead to sequestration of significant amounts of carbon in the deep ocean (Resolution LC-LP.1(2008) s. Annex 2). Experiments such as LOHFEX are intended to, and actually mimic, natural processes of iron input (dust outfall events, fleets of melting ice bergs, advection of iron-rich coastal water to the open ocean). Therefore these relatively small scale experiments - as discussed in detail below in section 2 - inherently carry no risks because their effects are similar to a short lived natural bloom. This has been clearly demonstrated by the results of field investigations and previous experiments. Indeed, measurements from ice and sediment cores indicate that annual iron input in the form of dust outfall during colder, drier ice ages to a square metre of Southern Ocean (SO) surface was ten times larger than iron input to the area affected by present experimental addition.

The LOHAFEX experiment will assess risks arising from prolonged fertilization, where extrapolation from a short-term, spatially restricted event makes sense. The data are urgently required to parameterise current models designed to assess the effects of large-scale fertilization deliberately applied to sequester significant amounts of carbon.

Commercialisation of OIF in the carbon credit market carries with it the additional, inherent risks if it will be carried out with little if any regard for the environment. This justified concern is the root cause of the scepticism raised by OIF in the science community and in the public. Indeed, previous experiments show that the response of fertilised plankton differs from case to case and that a set of complex factors governs the magnitude of the sinking flux. It is thus highly unlikely that it will ever be possible to set a quota of carbon per tonne of iron added, rendering the technique unsuitable for commercialisation. For a critical discussion on commercialisation of OIF see (Smetacek et al. 2008).

LOHAFEX will significantly enhance knowledge in many sectors of oceanography and marine biology, but it will also highlight the many uncertainties not yet appreciated that are associated with large-scale ocean ecosystem manipulation. Rather than opening the door for wanton speculation (an era now ignominiously ended) LOHAFEX will contribute to describing the risk of OIF commercialisation.

1.1. Scope of the Problem

A number of risks to the global environment have been invoked in association with large-scale OIF in the literature:

- Production of more powerful greenhouse gases than CO_2 such as nitrous oxide (N_2O) and methane (CH_4).

- Excess production by fertilized phytoplankton of trace gases such as halogenated hydrocarbons that can have an effect on the stratospheric ozone layer.
- Stimulation of toxic algae or enhanced toxin production in less toxic species as a result of OIF which might possibly have an effect on local fauna.
- Impairment of the organisms from bacteria to fish living in the deep sea and benthos (organisms of the sea floor) by lowering oxygen content of their environment. Initially their activity would be enhanced by the increase in their food supply, but if the rate of oxygen supply by advection of new, oxygen-rich water is lower than its consumption by organisms living off the enhanced particle rain, it will eventually lead to oxygen depletion and result in their displacement by communities adapted to suboxic to anoxic conditions. If this occurs in the subsurface layer, it would lead to production of N_2O and CH_4 and their release to the atmosphere.
- Reducing productivity in upwelling regions of low latitudes by reducing the nutrient concentrations in their source waters which is Antarctic surface water. If OIF works, nutrients will be sequestered in the deep sea and sediments for longer time scales together with the carbon to which they are bound.

None of these risks have been observed in the previous small-scale, scientific experiments. No harmful environmental developments have been detected nor have such experiments been suspected to produce such effects. They can only be expected when the plankton system is being altered over prolonged periods of time and on a sufficiently large scale. To date there are no assessments on the temporal or special scales of OIF that can potentially lead to the above mentioned risks. This was stated by the UNESCO Intergovernmental Oceanographic Commission (IOC) ad-hoc Consultative Group on Ocean Fertilization: *"We do not yet have the level of understanding of the marine environment needed to develop a set of specific regulations that would safeguard the ocean environment from fertilisation-type activities."* (LC 30/INF.4 Annex 1) (s. Annex 1). The LOHAFEX experiment will address these potential risks by applying advanced methodology that goes beyond the scope and analytical potential of previous experiments. It is therefore well placed to address the highly relevant questions required for the evaluation of impacts of OIF. While the results of LOHAFEX are expected to be useful in developing models to evaluate the risks associated with large-scale, long-term experiments, it is shown below that the experiment itself is of such a small magnitude that it is highly unlikely to have any detrimental effects on the environment, ecology or humans involved in it.

2. SITE SELECTION PROCESS AND SITE CHARACTERIZATION

The region selected for the experiment differs from the rest of the Antarctic Circumpolar Current because of its higher productivity and its location downstream from an extensive land mass – the Antarctic Peninsula – but also the island of South Georgia. This region has been intensely studied for decades both by research vessels and the careful evaluation of satellite images of chlorophyll concentration as a measure of phytoplankton biomass and productivity. Since iron fertilization experiments have unambiguously shown that iron limits productivity in the HNLC Southern Ocean (SO), it follows that an enhanced iron supply through contact with land masses must be responsible for the higher productivity in this region. The coastal influence of the overlying water is documented by the presence of spores of coastal, Hyalochaete species of *Chaetoceros* (oceanic species of the subgenus *Phaeoceras* do not make spores) that extend in a tongue from the Peninsula tip across the ACC to about 15 °W (Abelmann et al. 2006). Spores are absent further to the East suggesting that their presence indicates the current limits of coastal-water influence on perennially iron-limited oceanic water. Sediment cores show that their spores extended as far East as 45° E during the much colder, drier hence dustier last ice age, indicating higher productivity than today in this extensive region. Testing the iron hypothesis, which proposes that glacial/interglacial changes in atmospheric CO_2 levels were regulated by concomitant changes in Southern Ocean (SO) productivity, is one of the aims of LOHAFEX. Therefore, to test the validity of *Chaetoceros* spores as a proxy for higher productivity it is intended to locate the experimental site in an oceanic region with significant admixture of coastal water containing these neritic species. The downstream gradient of various radon isotopes, an indication of contact with continental crust, will also be measured as a proxy for coastal influence.

Waters of South Georgia are marked by high iron and chlorophyll concentrations throughout the year which is why iron addition will not have much effect. Neighbouring oceanic regions, where the experiment is to be located, exhibit higher productivity only during the spring bloom of phytoplankton and are as barren as the remainder of the ACC during the summer months, as current satellite images already demonstrate. It is likely that the decline in productivity is due to selective loss of iron following sinking of the spring bloom.

Two previous fertilisation experiments Eisenex and EIFEX carried out from RV POLARSTERN have shown that placing the experimental patch in the centre of a stationary eddy prevents the patch from being advected and dispersed by the strong currents in the Atlantic Sector of the ACC. To contain the iron fertilisation within the core of an eddy also helps to monitor the effects of the fertilised waters and to avoid impacts on surrounding areas. Eddies are formed by shear instabilities of frontal jets flowing round a rotating core of water. They can be cold or warm core eddies depending on the provenance of the core water with water temperature between 6 to 12°C. In cyclonic eddies the water is from the south, hence has higher silicon concentrations than the warmer cores of ant-cyclonic eddies. Preferably a cyclonic eddy should be chosen for the experiment in order to avoid Si depletion. However, the main criterion for eddy selection is its stability (it has to last for about 2 months) and retention of water within the closed core. The previous experiment EIFEX was located in such a stable eddy which enabled to follow the flux of particles from the surface patch through the deep water column down to the sea floor over the 35 days of the experiment. Altimeter images indicate that the eddy maintained its position and integrity over 6 months.

The suitability of eddies in the region of the experiment is currently being assessed on the basis of satellite images of sea-surface height (altimetry) and on models of the circulation within the closed core initiated with data derived from satellite altimeter observations. Three eddies within the region suspected of containing *Chaetoceros* seem suitable but have to be proven perfect by means of on-site measurements.

In addition, the site was selected in this general part of the Southern Ocean (SO) as it provides comparability to the previous iron fertilization experiments Eisenex and EIFEX carried out in the Atlantic sector of the ACC. It allows cross-comparison of results and provides a broader basis for the assessment of critical processes.

The region selected for the experiment is expected to exhibit the following conditions:

1. High concentrations of the nutrients nitrate, phosphate and silicate. All nutrients will be approximately 25 % lower than in the classic HNLC ACC of the same latitude.
2. An iron-limited, low production ecosystem characterised by the presence of typically coastal phytoplankton species.
3. A fairly large zooplankton population stimulated by the spring bloom but now food-limited by the decline in phytoplankton biomass.

The selected site will be outside the area of the Antarctic Treaty and be located north of the CCAMLR convention area 48 that extends to 50°S in the targeted region north-east of South Georgia.

3. EXPOSURE ASSESSMENT

3.1. Spatial Scales

The UNESCO-IOC Consultative Groups on ocean fertilisation states: *"The size of the activity is not the only factor to consider. An ocean fertilisation activity might be damaging even if conducted over one square kilometre (for example over a coral reef) just as another ocean fertilisation activity might be benign even though conducted over many thousands of square kilometres."* (LC 30/INF.4 Annex 1) (s. Annex 1). The impact of an experiment has to be assessed in context with the total area and characteristics of the targeted environment. Therefore, a fixed size cannot be determined to apply for all types of scientific experiments and the definition of "small-scale" needs to be assessed on a case by case basis. Section 1 outlines the potential risks that have been discussed in the literature. These potentially detrimental effects are of course linked to the magnitude of the iron input and have as yet not been observed so far in the previous small-scale scientific experiments.

In previous iron fertilisation experiments, the Eisenex and EIFEX, the iron enhanced patches were located within an eddy to avoid entrainment by frontal jets and there they maintained their identity until the ship had to leave (3 and 5 weeks respectively). The EIFEX patch was diluted by admixture of water from the surroundings by spreading in the course of the 35 days of the experiment. Sampling was carried out in the centre of the patch with the highest chlorophyll and lowest CO_2 concentrations but the extent of dilution could not be adequately determined because the tracer SF_6 was not added to the iron solution as in other experiments. Ascertaining the dilution rate is necessary for quantitative analyses of element fluxes. In an eddy with a homogeneous closed core, dilution occurs only along the periphery of the patch; so the larger the initial patch, the longer its centre will be protected from dilution. For this reason and because LOHAFEX will last 10 days longer, it was decided to establish a patch about double that of EIFEX using 20 instead of 7 tonnes of technical grade iron sulphate. The rate of spreading of the patch will also depend on its placement. If, by any unforeseen circumstances, the eddy will dissolve early in the experiment, of if the patch gets transported out of the eddy, we expect a severe dilution of the added iron, so that it will be impossible to see any reaction of the plankton. In this case a re-seed of a new location will allow the expedition to perform at least a short-scale experiment.

The targeted region for the LOHAFEX experiment lies in the northern part of the Antarctic Circumpolar Current (ACC). The ecosystem of the ACC can be considered as a broad band hydrographically linked by the current system and with similar plankton communities. The total size of the ACC is 50,000,000 km^2. It is interspersed by about 150 single islands (South Shetland Islands, South Orkney Islands, South Georgia, South Sandwich Islands, Bouvet Island, Crozet Islands, Kerguelen, Macquarie Island, Antipode Islands, Auckland Islands, Bounty Islands, Campell Islands, Prince Edwards Islands, Saint-Paul Island, Archipelago of Tristian de Cunha) and in contact with the land mass of the Antarctic Peninsula and South America that introduce coastal plankton. These land masses as well as melting ice bergs and to a lesser degree dust input from land supply iron to this ecosystem. Therefore, increased iron concentrations, albeit episodically or seasonally restricted, are a regular feature of this environment.

In respect to the spatial scale, the initial area of the experiment (300 km^2) was considered to be a small-scale experiment in comparison to the 50 million km^2 covered by the ACC. Any exposure of the manipulated patch to its surroundings is negligible.

3.2. Temporal Scales

The temporal exposure is limited to the actual iron enrichment (2 days) and the development of the bloom. Previous experiments indicate that fertilised blooms have a lifetime of up to 2 months. Thus the SOIREE bloom was observed as a crescent of higher chlorophyll in satellite images for a month but cloud cover prevented longer surveillance. The SOFEX north patch was entrained by a frontal jet and stretched band-like along several 100 km but only a few kms wide. The SOFEX south patch remained fairly rounded but its eventual disappearance could not be monitored. The fate of the Eisenex bloom could not be followed and in the EIFEX bloom species-specific sinking events commenced 24 days after fertilization and were ongoing on day 35 when the ship had to leave the site. However satellite images and a subsequent visit to the eddy 45 days later indicated that it had vanished from the water column by that time (manuscripts under review). LOHAFEX has about 45 days in hand to study the bloom from beginning to end.

4. EFFECTS ASSESSMENT

4.1. Introduction

Fertilization experiments to date show that the effects on the environment are similar to those of natural blooms and are short-lived (about 2 months). The fertilized area is so small (300 km^2) that, if not placed in the centre of a stable water mass, e.g. the centre of a stationary eddy, it will be quickly dispersed by mixing with surrounding water. The experimental design for the addition of iron is detailed in the cruise planning report (s. Annex 4).

Iron fertilization is expected to stimulate especially the growth of coastal species and lead to an increase in their biomass to about the magnitude of the previous spring bloom. The growing phytoplankton will take up a quarter of the nutrients after about 4 – 5 weeks until iron limitation is reached. The increase in food will stimulate further growth of the zooplankton. At present it is still unresolved how much of the enhanced biomass will sink out of the surface layer and to which depths the sinking particles reach before they are used as food by the deep sea organisms. The portion sinking out on the sea floor at around 4,000 m depth will also be used as food by organisms on the sea floor (benthos). A small fraction will eventually be buried in the sediments. The sedimentation and the burial of organic carbon as produced by LOHAFEX will be of similar magnitude as the export of natural blooms. Therefore, this is not expected to have a detrimental effect on the benthos. A major aim of the experiment is to quantify these processes with state-of-the-art instruments and methodology.

Another estimate of the possible effects can be obtained by comparison with naturally fertilized regions such as along the Polar Front south of the continents Africa, Australia and S. America, or through melting ice bergs that leave behind them swathes of higher productivity. Such an “ice-berg swathe” of at least 600 km breadth reflected in high iron concentrations (twice as high as normally attained by artificial fertilization) which led to build-up of phytoplankton biomass in the range of experimental blooms, was studied during a RV POLARSTERN cruise in 1992. The results were published in Nature and other journals (de Baar et al. 1995). The length of the bloom could not be determined due to the absence of a suitable satellite but it must have been several thousand kms long.

4.2. Effects on Biogeochemistry

Possible effects on the environment are assessed to be as follows:

1. Twenty tonnes of ferrous sulphate when applied to an area of 300 square kilometres, and assuming a mixed layer of 100 m thickness will enhance the dissolved iron concentration by a maximum of 2.4 nanomoles per litre. This is several factors lower than natural iron levels in most coastal marine waters of 60 nanomoles per litre (Nolting et al. 1991). This concentration is so low that most analytical laboratories in the world cannot measure it accurately. In addition the size of the fertilized patch is considerably smaller than the impact of melting icebergs that may leave a swathe of several hundred kilometres breadth of enhanced iron concentrations (see above). Sulphate is a major constituent of sea water occurring in concentration of around 28 millimoles per litre. The experiment adding 2.4 nanomol per litre will thus not change its concentration measurably. The ferrous sulphate ($FeSO_4$) used for fertilization by LOHAFEX is of the same chemical purity as that sold in gardening shops in 5 - 10 kg bags as a lawn additive. No risks are associated with its use either for humans, livestock, soil organisms and their mammal and bird predators or ground water, although application on a square metre basis on land is orders of magnitude higher than in OIF. Any minor impurities in the $FeSO_4$ will be greatly diluted i.e. their concentrations will be two orders of magnitude lower than those of iron and sulphate. SF_6 will be added as inert chemical tracer as standard procedure in many ocean experiments. Side effects on biology are not known. Thus, the experiment will not lead to any ‘chemical’ pollution.
2. The fertilized waters, although located offshore, have been previously in contact with South American or Antarctic Peninsula continental coastlines and the island of South Georgia and contain coastal plankton species that are adapted to high iron concentrations. These areas of the Southern Ocean (SO) are frequently occupied by blooms of similar composition and biomass per square metre as reflected in satellite images. This is most likely caused by sporadic or seasonal natural inputs of iron. Therefore, phytoplankton blooms of the size and the duration created by the LOHAFEX experiment are a regular feature in this region.
3. Assuming a C/Fe ratio of 1,000-15,000 the additional organic carbon produced within the LOHAFEX patch will be 0.24-3.6 moles or 2.9 – 43 g C per square metre. If we assume, as a generous estimate, that 50% of this carbon sinks below the mixed layer and is completely degraded within a 1 km-thick water column, the average oxygen decrease in this water column will be 0.15 – 2.3 micromoles per litre. This is a reduction of less than 2 % of the oxygen concentration in sea water and around the precision of the titrimetric Winkler procedure. An oxygen decrease of this magnitude will not cause any deleterious effect on the environment/ecology because the waters at the experimental site are well oxygenated (minimum dissolved oxygen is around 200 micromoles per litre). With this negligible oxygen change the production of nitrous oxide and methane will be insignificantly affected (e.g. nitrous oxide concentration may increase by 0.02-0.3 nanomoles per litre, while methane production will be even

less affected in well-oxygenated waters). Dimethyl sulphide is also expected to be produced by phytoplankton blooms, but its production will actually be beneficial. Production of other trace gases is harder to evaluate, but with the data available from previous experiments and given the small scale of LOHAFEX, the overall production of these gases is expected to be quantitatively insignificant.

The LOHAFEX experiment is therefore considered to exert no detrimental impact on the biogeochemistry of the environment as the amount of iron applied and the variability of other biological and chemical parameters are expected to be well within the natural limits of iron inputs and variability.

4.3. Effects on Species, Communities, Habitats and Processes

In all experiments the bulk of the biomass increase was due to diatoms from both centric and pennate lineages. Organisms of the microbial food web appeared to enhance their activity but, with the exception of bacteria, no significant change in biomass has been reported. That diatoms and the colonial flagellate Phaeocystis dominate SO blooms with much less fluctuation in the microbial food web was first postulated by Smetacek et al. (1990) and has since been borne out by field observations and fertilisation experiments. So far the DMS-producing Haptophyte Phaeocystis has not played a significant role in fertilized blooms, but that is likely to change if the grazing pressure on young, vulnerable colonies is lowered. This needs to be studied because a Phaeocystis bloom – they are the rule in the Ross Sea but rather exceptional in the ACC despite constant presence in the plankton - will affect the magnitude of vertical flux and DMS production. Its effect on the food web structure has yet to be ascertained.

Although the iron-induced blooms all stimulated local, common species of diatoms, patterns of dominance differed between experiments, indicating complex driving factors and highlighting our dearth of basic knowledge of the ecology of plankton in general. The fact that a very broad range of common species responded to iron fertilization indicates that none of them is sensitive to enhanced iron concentrations. Biodiversity and species dominance of the biomass of natural blooms also varies widely, although it is possible to separate some 15-20 species more likely to build up biomass from the >100 species that always occur at low concentrations. These bloom-forming species differ widely amongst each other in terms of lineage and thickness of the silica cell wall so the postulated shift in the C:Si ratio based on laboratory experiments attributed to iron-fertilised diatoms making thinner shells could not be verified by in situ experiments. Instead it appears that species composition – the proportion of thick- to thin-walled species, rather than iron-limitation or –sufficiency determines the bulk C:Si ratio of diatoms. Because of its potential impact on grazers and the ocean’s silicon cycle, further studies are needed.

The small, ubiquitous crustaceans of the zooplankton – copepods – are reported to be attracted to fertilised blooms. During EIFEX common species increased growth and reproduction significantly. Thus, blooms are likely to have a beneficial effect on copepod populations. In contrast, salps disappeared from the patch water column of EIFEX suggesting that they do not respond to increasing food supply and are rather adapted to oligotrophic waters. The general decline in krill stocks and concomitant increase in salps around Antarctica has been interpreted as a sign of decreasing overall productivity. Since SO productivity is a function of the iron supply, it is feasible that OIF in the krill habitat could counter this alarming, ongoing trend of steady krill decline and their replacement by salps (Smetacek et al. 2008). It has also been speculated that the decline in krill is likely to jeopardise recovery of the populations of great whales that depend on krill for food. Testing this hypothesis will require larger-scale, longer-term experiments, thus is beyond the scope of LOHAFEX. It now appears unlikely that we will encounter krill in the eddy selected for LOHAFEX so will not be able to ascertain the effect of food enhancement on egg development as could be shown for copepods during EIFEX.

It is concluded that in the experimental site local diatom species will grow and possibly succeed each other in the course of the experiment. Copepods will multiply and salps probably decline. By the end of 2 months the fertilised patch will have reverted to the conditions in surrounding unfertilised water leaving behind no lasting changes to the environment. OIF experiments provide a powerful tool to investigate the relevant processes under field conditions, i.e the presence of intact grazer populations not possible in laboratory or mesocosm scales. It is likely that copepod reproduction will be stimulated but the fate of the larvae is unknown as the bloom will have disappeared well before they reach maturity. Salps are likely to be deterred by the bloom. These latter hypotheses need further testing. All biological effects are within the natural variability of the ecosystem and are considered to be not detrimental.

4.4. Human Health and other Legitimate Uses of the Sea

The study area is remote and thus there is no risk of any impact of a small-scale experiment of this size on human health or other uses, because, as mentioned above, it is expected to produce changes well within the natural variability. Its location in the eastward flowing, open ACC precludes its contact with any human settlements over the course of its lifetime.

The scientists and technicians handling the Fe SO4 on board during fertilization will be wearing special suits and masks to avoid ingestion, inhalation or contact with the eyes as a precaution because, although non-toxic, exposure over an hour‘s duration could lead to irritation of mucus membranes.

4.5. Uncertainties and Data Gaps

A considerable body of literature has accumulated on the results of OIF experiments, however, the fate of the bloom biomass is still uncertain. Other data gaps exist particularly in the species response to iron fertilisation. All aspects will be addressed during LOHAFEX by reputed scientists in their respective fields of expertise from bacteria to zooplankton.

4.6. Conclusions on Effects Assessment

It is concluded that the LOHAFEX experiment will not have any unnatural impact on the environment, ecology or human health. Its effects will range from negligible to benign and innocuous.

5. RISK CHARACTERIZATION FOR IRON FERTILIZATION

5.1. Risk Definition

The potential risks that may arise from the fertilisation with iron were identified by previous experiments and are published in the literature. In the worst case of serious impact the following risks may be encountered:
- Production of more powerful greenhouse gases than CO_2 such as nitrous oxide (N_2O) and methane (CH_4).
- Excess production by fertilized phytoplankton of trace gases such as halogenated hydrocarbons that can have an effect on the stratospheric ozone layer.
- Stimulation of toxic algae or enhanced toxin production in less toxic species as a result of OIF which might possibly have an effect on local fauna.
- Impairment of the organisms from bacteria to fish living in the deep sea and benthos (organisms of the sea floor) by lowering oxygen content of their environment. Initially their activity would be enhanced by the increase in their food supply, but if the rate of oxygen supply by advection of new, oxygen-rich water is lower than its consumption by organisms living off the enhanced particle rain, it will eventually lead to oxygen depletion and result in their displacement by communities adapted to suboxic to anoxic conditions. If this occurs in the subsurface layer, it would lead to production of N_2O and CH_4 and their release to the atmosphere.
- Reducing productivity in upwelling regions of low latitudes by reducing the nutrient concentrations in their source waters which is Antarctic surface water. If OIF works, nutrients will be sequestered in the deep sea and sediments for longer time scales together with the carbon to which they are bound.

As outlined above the temporal and spatial scale of the experiment is assessed to be too small to develop these potential risks and to produce negative effects. Previous OIF experiments in this region did not show indications of these risks. Even though the LOHAFEX experiment will apply twice the amount of iron sulphate compared to the previous experiments to the selected eddy core, this addition is highly unlikely to cause any deleterious effects to the biogeochemistry or biodiversity. However, it must be noted that only a few OIF experiments have been conducted so far in the Southern Ocean (SO), and therefore relevant data from iron fertilization are still quite scarceand limited in detail. Moreover, these field data are mainly limited to deep-sea situations, and for short periods. Sustained iron fertilization over a large area might produce a different biogeochemical and ecosystem response that can only be predicted by larger, longer-term experiments. However this is beyond the scope of LOHAFEX.

5.2. Uncertainties and Data Gaps

A major uncertainty in the scientific assessment is the question at which level of iron fertilisation negative effects are to be expected. These levels will vary depending on the risk considered and they will also vary with location. As mentioned before, the scientific experiments carried out so far are too small to produce these effects. In order to develop protocols for risk assessment these questions have to be resolved. LOHAFEX will also not reach the level of detrimental effects due to the limited spatial and temporal size. Only the underlying processes can be parameterised in some of the mentioned risks and can be used to develop predictive models. Major research is still required to approach these questions and to develop modelling tools for assessments.

5.3. Conclusions

As detailed above (Section 4) we do not foresee any risk to the environment, ecology and human beings from the proposed LOHAFEX experiment. Therefore no measures or modifications of the process of iron fertilisation are proposed.

6. RISK MANAGEMENT

The risk management is based on the risks identified in Section 5. Although no negative effects to the environment are expected a detailed monitoring plan has been developed to follow the relevant changes. This monitoring is the basis for the scientific analysis of the processes. The bloom will be surveyed for the whole duration of its existence and therefore data are available for the whole period of the impact.

6.1. Monitoring

LOHAFEX will monitor a number of parameters that are indicative of potential risks. Although the changes are assumed to be minor in this type of experiment and not lead to environmental damage, the measurements will be able to indicate in which direction and at which time scales changes are occurring and which processes need to be monitored in future experiments. The information gathered in the fertilised area and in the adjacent unfertilised control site will be recorded and appropriately documented. A detailed description of the experimental design and the measurement strategy is given in the cruise planning document (s. Annex 4).

LOHAFEX will provide information directly or indirectly by monitoring the relevant variables and providing data for parameterisation of models aimed at assessing these risks.

- Dissolved oxygen will be measured on a routine basis on all water samples from the surface, mesopelagic and deeper layers. Oxygen/argon (isotope) ratios will also be monitored in the surface to determine net community production. In addition to the major greenhouse gases - carbon dioxide, nitrous oxide and methane - the following halocarbon trace gases will be measured during LOHAFEX: methyl iodide, carbon tetrachloride, chloroform, 1-iodopropane, 1-iodobutane, dibromomethane, bromoform, and diiodomethane. In addition dimethy sulphide will also be measured during the expedition.
- The species composition of bacteria, phyto-, protozoo- and metazooplankton will be closely monitored using microscopy, enhanced by the most recent molecular taxonomy techniques (molecular phylogeny, metagenomics, DNA bar coding, inter alia). The diatom genus *Pseudo-nitzschia*, the only diatom genus known to harbour species with toxic effects on the food chain leading to mammals, will be paid special attention by the experts on board. Samples for domoic acid (the toxin produced by this genus) will be taken for later analysis. The well-known toxic dinoflagellates are unlikely to appear but will also be under surveillance. Copepod egg viability will also be routinely assessed as a further indication of other noxious substances (e.g. aldehydes) in the enhanced food supply provided by fertilisation.
- All the macronutrients, pH and DIC will be routinely measured in the upper 500 m, and less frequently down to the sea floor. It will be possible to derive budgets of the ratio Fe added to C, N, P, and Si taken up and transported to depth. These data are needed to realistically parameterise existing biogeochemical ocean general circulation models (GCM) to predict the impact of CO_2 sequestration in the Southern Ocean (SO) on global nutrient budgets.
- Export of organic carbon to the deep ocean will be quantified in drifting sediment traps and via nutrient budgets. Sediment samples are taken by Multicorer to analyse the deposited algal material on the sediment surface. The latter cannot be used to quantify flux to the sediment due to lateral advection, but can indicate fast sinking components of the plankton system.

6.2. Site Selection

Maximum care will be employed to localise a suitable, stable eddy that will be fertilised in its core. Satellite altimeter data, modelling and direct measurement in the field prior to the experiment are used for this purpose. Since eddies are temporal structures the selection can only be carried out at the time of the experiment and in conjunction with on-site measurements to determine the start values of the relevant variables.

The stability of the eddy over at least 2 months is of major importance in order to contain the bloom in a well defined area and to prevent its spread to surrounding areas. This will ensure that the impacted water is contained within the eddy until the end of the bloom and adjacent areas are not affected. Monitoring of this fertilised patch and comparison to adjacent unfertilised waters is facilitated by this hydrographic feature that separates both.

Like all artificial and natural blooms the LOHAFEX bloom will be visible in satellite images and they are used to assess the temporal development in the wider field. They are posted on the web and every interested party can therefore follow the extent and concentration of the bloom and compare it with natural blooms elsewhere. The course of the experiment will be described in weekly reports posted on the internet.

7. OVERALL CONCLUSIONS AND IMPLICATIONS

7.1. Conclusions

The result of the environmental impact assessments leads to the conclusion that the effect of iron addition by the LOHAFEX experiment will be in the range of naturally occurring iron inputs, e.g. in the wake of islands or melting ice bergs. Any harmful effects to the ecosystem are not expected. The measurements carried out will be able to monitor all relevant variables that are required to follow the changes and to address potential risks. They will provide the urgently required information for the development of models for the assessment of OIF.

7.2. Compatibility of the Assessment Report with the London Protocol

The risk assessment and management for the LOHAFEX iron fertilization experiment as performed in this report is compatible with the considerations for evaluating ocean fertilization proposals by the Scientific Groups (LC/SG 31/16, annex 2 ,appendix 3) and the Revised Generic Waste Assessment Guidandance (LC 30/16) .

8. LITERATURE

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9. LIST OF ANNEXES

Annex 1 London Convention/Protocol 2008
LC 30/INF.4
OCEAN FERTILIZATION
A compilation of recent international statements, agreements and recommendations regarding ocean fertilization

Annex 2 London Convention/Protocol 2008
RESOLUTION LC-LP.1(2008)
ON THE REGULATION OF OCEAN FERTILIZATION

Annex 3 London Convention/Protocol
LC/SG 31/16 ANNEX 2
OUTCOME OF THE WORKING GROUP ON OCEAN FERTILIZATION

Annex 4 AWI Expedition Programme No 82, November 2008
Cruise ANT-XXV/3 LOHAFEX

Annex 5 REPORT OF THE CONFERENCE OF THE PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY ON THE WORK OF ITS NINTH MEETING, Bonn, 19–30 May 2008