Understanding the potential of ocean iron fertilization to reduce atmospheric carbon dioxide.

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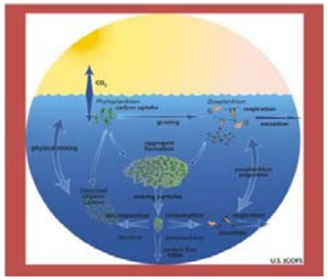
Annual flux of anthropogenic carbon.

The oceans take up about a quarter of the annual release of anthropogenic carbon. This flux is by the "solubility pump" of CO_2 across the air-sea interface and is positively related to the difference in concentration between the atmosphere and the sea. Uptake is a slow process due to complex inorganic carbon reactions in the ocean.



Once dissolved in the ocean, phytoplankton take it up during growth. Some of this carbon enters the food chain and a proportion is exported from the surface ocean to the lower parts of the water column. This is as a result of particle sedimentation, diffusion of dissolved carbon or animal migration. This is termed the "biological pump" (figure). "Export" is considered as the loss of material from the upper mixed layer (eg 100m) but much of this is remineralised to CO_2 in water which returns to the surface in a short period of time (eg 6 months). From the perspective of climate change mitigation, the carbon must be "sequestered" which we define as being removed from atmospheric interaction for more than 100 years and this therefore demands transport to the deeper layers.

The principle behind Ocean Iron Fertilisation (OIF) as a climate change mitigation strategy is that the biological pump (above) could be enhanced so as to sequester more carbon from the upper ocean and hence encourage oceanic uptake of CO_2 from the atmosphere.

In most areas of the ocean one or more of the macronutrients (nitrate, silicate and phosphate) is fully used at some time during each year. In other areas this cannot be achieved due to limitation by the micronutrient iron or by insufficient light. These are the so-called High Nutrient Low Chlorophyll regions (HNLC). In other areas referred to as Low Nutrient Low Chlorophyll areas (LNLC), nitrogen is also limiting but there is insufficient iron to support nitrogen fixation. In both these cases addition of iron enables production to proceed until another nutrient is limiting such as phosphate.

As a micronutrient, small quantities of iron are required in order to stimulate production demanding low costs for mining, transportation and administration.

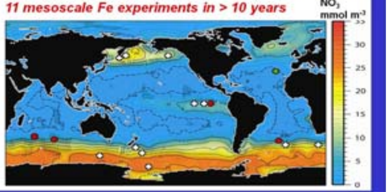
On the decadal scale, with continuous and excess fertilisation by iron, productivity and hence sequestration is limited by the rate of supply of the macronutrients from the deeper water. Other ocean fertilisation strategies have been proposed which involve the supply of macronutrients from deep water by pumping or from land.

Conclusions from previous OIF:

In response to iron fertilisation:

1. Phytoplankton always bloom
2. Export flux is probably enhanced
3. Sequestration flux to deep water may be enhanced.
4. Physical and temporal extent of experiments insufficient.
5. Physical oceanography not adequately understood

Previous iron fertilisation studies. *(Boyd et al. 2007)*



Requirements for future iron fertilisation experiments:

1. Duration must be long enough for ecosystem to respond and for CO_2 uptake to increase (months)
2. Duration should be long enough to examine interannual variation during repeated fertilisation (years)
3. Fertilised patch must be large enough to avoid "edge effects" (eg 200 x 200Km)
4. The very best biogeochemical models embedded in physical models must be employed to design and manage the experiment and then to interpret the results.
5. In contrast to previous experiments, the goal of the experiment should be to assess the effect of fertilisation on carbon sequestration (removal from atmosphere for more than 100 years).
6. All potential unintended consequences must be addressed and in particular the generation of climatologically active bio-gasses. As can be seen bottom left, results from previous studies have been inconsistent.

The modelling framework:

There are 2 distinct but equally important modelling time scales required in order to support and interpret the observations. Both demand high resolution physical models with embedded biogeochemistry. Of the numerous models currently available, it is anticipated that several have the potential to be developed for these purposes. By using a diversity of models confidence in the conclusions will be enhanced:

Short term and Real-time: Significant developments in modelling will be required in order to select the site and coordinate the experiments as they progress. This will involve data assimilation to track the migration of the fertilised patch and the process changes within it. These models will also be used to manage sampling to ensure the greatest efficiency.

Long-term: *For understanding if the carbon will be sequestered (>100 year).* This will serve as the central activity for our OIF long-term modelling program and will be applied initially to a number of OIF field experiments that have already taken place.

The importance of physical oceanography:

In order to achieve sequestration and not just enhanced export flux, there are a number of crucial factors directly associated with physical oceanographic processes which must be understood and properly modelled. The dynamics of ocean subduction and deep water formation will be important foci of our study as they determine to a significant extent the significance of the observations. Enhanced particle export is not enough:

1. After fertilisation and subsequent enhanced productivity, the water must stay in contact with the atmosphere for a sufficiently long time to allow dissolution of CO_2 (months)
2. The water must then downwell or be mixed downwards sufficiently quickly so that it does not move into an area which is fertilised naturally.
3. The rate of supply of new nutrients must be very well characterised.

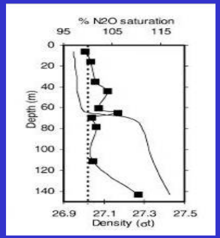
Risk of unintended consequences

Future experiments must address all unintended consequences both by observation and modelling and these considerations must have a duration of at least 100 years.

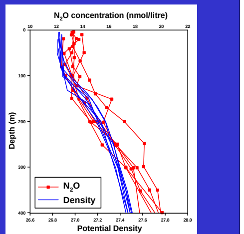
Examples of potential side effects of fertilisation:

Eutrophication	Ecosystem structure modification
Anoxia	Toxic bloom stimulation
Ocean acidification	Generation of biogasses (Right)
Global iron cycle change	

Vertical profiles of N_2O after iron fertilisation



SOIREE: *Law and Ling 2001*



EIFEX: *from Walter et al 2005*

Dotted line: Saturation
Solid line: Water density
Squares: N_2O

Evidence of N_2O build up at the pycnocline during SOIREE (left) but not during EIFEX (right). This shows the variable responses to OIF and emphasises the need for further research before conclusions can be made.