

Engineering Ocean Nourishment

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Abstract – The annual productivity of the ocean is limited by the availability of nutrients. Ocean Nourishment® is the concept of purposefully introducing nutrients to the surface ocean to sequester carbon dioxide and increase the sustainable supply of marine protein. The engineering challenges are to inject the nutrients so that they diffuse to an appropriate concentration while being consumed by phytoplankton. Ship based supply of nutrients from onshore manufacture is assumed. Broadcasting granular material onto the surface of the ocean is examined. The depth over which the prills or grains dissolve can be controlled by the diameter and density of the particles. Design considerations are discussed.

Index Terms - climate change, ocean engineering, ocean nourishment, diffusion

I. Introduction

A rapidly changing climate will require many adjustments to the physical and social infrastructure of the world. Some regions will need to depopulate, some regions will become more desirable places to live and create economic activity. International agreements have been put in place to limit the rate of change of the global warming and now engineers need to devise methods of both slowing climate change and adapting to the new climate.

The two main determinates in setting the temperature of the Earth is the amount of solar energy intersecting the disk of the earth and the amount of that heat trapped within the atmosphere. Greenhouse gases play a role in retaining solar radiation and the focus of most climate management schemes is adjustment of their concentration. The most important greenhouse gases are water vapour and carbon dioxide. It is well accepted that carbon dioxide concentration is rising rapidly due to fossil fuel burning. The direct human impact on water vapour is usually ignored.

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It already stores a very large amount of carbon in solution and a modest increase in the ocean carbon storage would have a significant impact on the atmospheric concentration of carbon dioxide.

This paper looks at the engineering issues in using the Ocean Nourishment® concept to increase the flux of carbon from the atmosphere to the ocean. It involves providing the nutrients that presently limit the growth of vegetable matter (phytoplankton) in the upper ocean in order to store more carbon and increase the base of the marine food chain with an ultimate goal of increasing sustainable fish catch. Ocean Nourishment relies on biomimicry for its inspiration, where carbon is transferred through phytoplankton, to zoo plankton, to fish. Further elaboration is provided in Jones and Young (1997). The harvesting of fish provides a small return of carbon to the atmosphere, around 1%.

The organic carbon cycle is driven by the conversion of the inorganic carbon (carbon dioxide) that is dissolved in the upper ocean to organic matter by phytoplankton. Some vegetable matter sinks under gravity to the deep ocean while some is converted back to inorganic carbon and nutrients. This process of photosynthesis in the surface ocean continues until all of a critical nutrient is exported from the upper ocean and limits further growth. Fig 1 illustrates this cycle and the remineralisation of the sinking organic matter. Eventually the carbon returns to the upper ocean where it again undergoes photosynthesis with the aid of chlorophyll. The aim of Ocean Nourishment is to increase the amount of carbon involved in this cycle.

The energy needed to produce organic matter from carbon dioxide is provided by the sun while gravity moves the newly created vegetable matter to the deep ocean. While the provision of nutrients involves the use of energy both for their transport and transformation, the small fraction (some 15%) of nutrients in marine biomass (the rest being mostly carbon) suggests that Ocean Nourishment might be much more cost efficient than more traditional concepts such as capture, transport and storage of carbon dioxide.

II. Ocean Nourishment

The storage of carbon in the organic carbon cycle of the ocean has been the subject of a number of patent applications, eg Markels (1999) or Jones et al (2007). The first involves the idea of providing iron to those regions of the upper ocean with adequate macro nutrients in order to increase new primary production and to export carbon to the deep ocean. Because of the way iron is scavenged (Johnson *et al* 1997) by sinking particles, it is believed that the addition of iron leads to short term storage of carbon (Peng and Broecker, 1991, Markels and Barber, 2001).

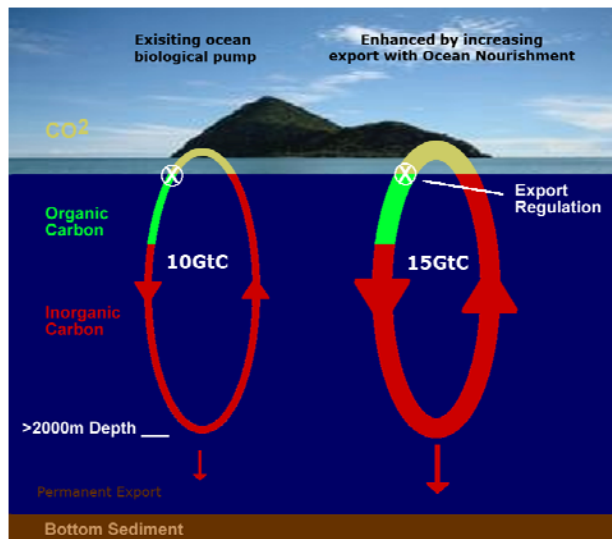


Figure 1: Oceanic Organic Carbon Cycle, existing and enhanced by increasing export. Orange = CO₂ in atmosphere, Green = CO₂ in organic matter, Red = CO₂ in solution. Small arrows represent permanent deposition in the deep ocean of carbon on the sea floor.

When the regenerated nutrients return to the photic zone they may not be able to retain the carbon because iron is again in short supply. As well, iron fertilisation may just be stealing macro nutrients from another region as the now depleted surface waters are advected by the large ocean gyres.

For longer term storage and confidence that there is global net storage at all (Gnanadesikan et al, 2003) macronutrients must be added, as revealed in Jones et al (2007). The practicality of nourishment of the ocean using reactive nitrogen was examined by Jones and Otaegui (1997). It has been shown in Jones (2007) that the macro nutrients nitrogen and phosphorus are sufficient to increase primary production in much of the world's ocean. Since the added macronutrients are recycled in the upper ocean until they are all exported to the deep ocean, high storage efficiencies can be expected.

III. Design Parameters

The biggest engineering challenge in providing nutrients to the photic zone of the ocean is that of ensuring the change of concentration due to dilution and consumption by phytoplankton are adequate. The initial concentration needs to be not so small to make measurement difficult and not so large as to produce a risk of creating harmful algal blooms. It is desirable to limit the flux per unit of surface area of carbon to the deeper ocean to avoid depleting the oxygen level in the thermocline.

One can consider a design to store about 5,000 tonnes per day of carbon 5×10^9 g/d. With ample sunlight and nutrients the concentration of phytoplankton grows exponentially. Let us assume the concentration doubles each day. Then suddenly one nutrient is exhausted and growth stops. In this simple model half the phytoplankton mass is produced on the last day of growth. [...+2+4+8 =16] Let us assume this growth is over a region 25 Km x 20 Km then the current needs to be $20/24 \text{ Kmhr}^{-1}$ which is 0.23 ms^{-1} . The uptake of carbon on the last day is $5 \times 10^9 \text{ g}/2 \times 500 \text{ Km}^2 = 5 \text{ gCm}^{-2}\text{d}^{-1}$. For a 50 m deep

photic (mixed layer) zone, $5 \text{ gm}^{-2}\text{d}^{-1}$ of carbon is $100 \text{ mgCm}^{-3}\text{d}^{-1}$ and needs $100/7 \text{ mgNm}^{-3}$, divided by the molecular weight (14) = $1 \text{ mmoleNm}^{-3}\text{d}^{-1}$ or $1 \text{ } \mu\text{moleL}^{-1}\text{Nd}^{-1}$. The total conversion of inorganic to organic carbon therefore is 10 gCm^{-2} and N required is $2 \text{ } \mu\text{molar}(\mu\text{M})$. The last figure comes from assuming the Redfield ratio of the constituents in phytoplankton, a subject discussed by Michaels et al. (2001).

The 100 mg.m^{-3} increase of organic carbon on the last day is roughly an increase of $2 \text{ } \mu\text{gL}^{-1}$ Chla. Such rates of photosynthesis and chlorophyll level are typical of those seen in upwellings. In a situation of excess nitrogen, Berg et al (2001) found uptake rates of nitrogen equivalent to $30 \text{ mgCm}^{-3}\text{hour}^{-1}$ or 200 mgCm^{-1} per sun day for a chlorophyll level somewhat greater than our example.

The Engineering challenge therefore is to plan the introduction of nutrients at a location some days up-current of the desired position of maximum growth, in order to limit the concentration. Some key parameters are the current velocity, depth of the surface mixed layer, diffusion rate, and time until maximum phytoplankton biomass concentration is achieved. These variables are all environmental factors that the engineer has little practical way of manipulating. The primary variables at the discretion of the engineer are the initial area that is to be nourished and the initial concentration of the introduced nutrients, as well as the release location.

The initial concentration can be varied by altering either the amount of nutrients introduced or the sea surface volume over which those nutrients are deposited. It is desirable that a continuously operating Ocean Nourishment plant would be supplying a fixed amount of nutrient to the ocean each day to avoid an excessive requirement of storage capacity. Storage capacity could then be reserved for breakdown, production, or weather contingencies. Manipulation of the area of dispersion is therefore the most attractive method to achieve the desired results.

Two potential methods of distributing the nutrients into the mixed layer of the ocean are by pipeline or by ship. The high initial capital costs of the pipeline favour the use of transport by ships at the initial introduction of Ocean Nourishment. Ships provide a flexible option to broadcast the nutrients in a predetermined pattern. The final high productivity area will be set by the cross current sailing distance of the nutrient distribution ship.

IV. Controlled Diffusion

Using the time to maximum biomass we can work backwards from the target concentrations of chlorophyll considering the magnitude of dilution on the patch. If we use a ship based approach diffusion can be used to our advantage by nourishing in strips perpendicular to the current direction, then allowing diffusion and convective mixing over the mixed layer depth to even the concentration after n days. The process can be designed so that near uniform concentration is achieved as the patch reaches maximum growth.

To achieve the carbon conversion in the previous example we would aim for a total of $2 \text{ } \mu\text{M}$ of additional N to be available for phytoplankton uptake between the injection and location of maximum biomass. By considering diffusion alone in the

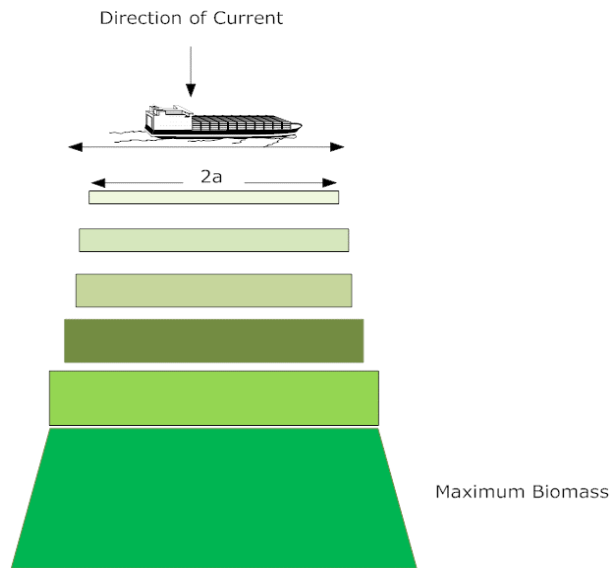


Figure 2: The upper strip illustrates the region into which prills are broadcast. The nourished water diffuses in both the down and cross current directions. After n days the concentration is near uniform along the axis of the current.

absence of uptake we would like a concentration $2 \mu\text{M N}$ at the planned location of maximum biomass. When there is both diffusion and uptake there should be no introduced nitrogen left at this location, as it will all have been consumed.

If we assume our strip spacing achieves a uniform concentration along the axis of the plume by the time of maximum biomass, then diffusion along the axis is of no consequence to the final average concentration. If we also assume a constant depth mixed layer, and that negligible nitrogen is lost through the thermocline and sea surface interfaces, then further reduction of concentration can be considered to result from lateral diffusion alone.

Modelling the turbulent diffusion by a co-efficient D and assuming the concentration follows Fickian diffusion laws, Carslaw and Jaeger (1959) provides the expression for the concentration at time t :

$$C(x, t) = \frac{1}{2} C_0 \left[\text{erf} \frac{x-k}{2\sqrt{Dt}} + \text{erf} \frac{x+k}{2\sqrt{Dt}} \right]$$

where x is the direction normal to the plume axis, and C_0 is the initial concentration in the region $-a < x < a$. The region $|x| > a$ is initially at zero concentration.

On the centreline of the plume:

$$C(t) = C_0 \cdot \text{erf} \left[\frac{a}{2\sqrt{Dt}} \right]$$

For initial injection strips of $a = 7.5 \text{ Km}$ and $t = 6$ days we find that the concentration on the centreline has dropped to 0.934 of its initial value for a turbulent diffusivity of $15 \text{ m}^2\text{s}^{-1}$. This is a dilution of 1.07. For problems with a length scale of 20 Km Csanady (1972) suggests diffusivities of this order.

A relevant source of data for verifying the theoretical calculations of diffusion are the 12 mesoscale iron enrichment experiments that were conducted from 1993-2005. The majority of these experiments used hexasulphurfluoride (SF_6) as a chemically inert tracer to distinguish the marked patch of water. The sampled SF_6 profiles during the experiments allow calculation of the dilution of the patch of nourished water. The average value of dilution across all experiments with published results was found to be 0.17 day^{-1} , calculated from Boyd et al. (2007). Using 6 days as an example, the growth of the patch is given by the factor $\exp(0.17 \times 6) = 2.8$. The enriched patch of oceanic water in the iron addition experiments consisted of geographical rectangles whereas in our design there is continuous nourishment to strips across the current. Once we have allowed the regions between the strips to diffuse together the nutrient diffusion will be constrained to diffuse laterally. Therefore we must modify the dilution rate to account for one-dimensional lateral diffusion giving $2\sqrt{2.8} = 1.7$. Calculating theoretically on the centreline for $a = 1 \text{ Km}$ and $t = 6$ days we find that the concentration on the centreline has dropped to 0.58 of its initial value using a turbulent diffusivity of $1.5 \text{ m}^2\text{s}^{-1}$ suggested by Csanady (1972) for a length scale $= 1 \text{ Km}$. This is a dilution of 1.7.

Culture bottle enrichments of natural phytoplankton stock from oligotrophic waters using nitrogen and phosphorous have been conducted (Jones, 2007). The time until maximum growth is dependent on the temperature and was found to vary from 4 days in the Sulu Sea to 8 days in colder latitudes such as the Canary Current in the Atlantic Ocean. (Harrison, 2007). Longer incubation periods increase the uncertainty of the engineering design by increasing the susceptibility of the enriched plume to change of currents and greater diffusion variability. This makes some locations more challenging than others. At a current of 40 cms^{-1} 8 days after injection the area of maximum biomass may occur some 280 Km down-current from the injection location.

To achieve the enhanced productivity patch of $25 \text{ Km} \times 20 \text{ Km}$ in our design example by day 6, we could use a cross current injection width $2a = 25/1.07 = 23 \text{ Km}$.

V. Injection Concentration

We now turn our attention to how best distribute the nitrogen. Although the nutrients are expected to be well mixed vertically within 24 hours due to convective mixing, an aim of the distribution process is to avoid high peak concentrations immediately after introduction of the nutrients. A patented technology of the Ocean Nourishment Corporation (Jones et al. 2007) is to distribute the urea into the sea in prilled form. A prill is a spherical grain of urea formed by cooling droplets of molten urea in an airstream.

The urea prills can be distributed into the mixed layer of the surface ocean by borrowing technology developed by the agriculture industry. With some modification agricultural spreaders can be used to broadcast the urea from the deck of a ship. Various sizes and classes of spreaders are available, most use the principal of centrifugal acceleration to propel granular material out in a fan type pattern from the source. The source generally consists of a spinning disk with vanes that is fed material by gravity from a hopper mounted above.

The design considerations in terms of the concentration immediately after injection are the volume of water the nutrient is introduced to and the quantity of nutrient. For the reasons outlined above we will consider that the quantity of nutrient is fixed by the design of the urea plant. The volume of water that contributes to the immediate concentration is therefore set by the fall depth of the urea prills and the broadcast area. An adequate broadcast distance is 20 m from the spreader and will provide a good separation between prills. As they fall the prill dissolves leaving behind a plume of enriched water which immediately starts diffusing laterally. A maximum desirable depth for dissolution to be complete is less than the depth of the mixed layer. Nutrient introduced below this level may not contribute to increased carbon drawdown as water below the thermocline is not in communication with the atmosphere. As the mixed layer varies throughout the year the annual minimum will form a design constraint such that the manufacturing rate need not be varied seasonally.

The fall depth of the spherical particles is a function of the fall velocity and dissolution rate. Commercially available prilled urea contains a bubble of air which lowers the bulk density of the sphere from that of solid urea. As the prill sinks and dissolves and the outside circumference reduces, the volume ratio of air to urea increases, therefore bulk density decreases as does the relative density difference between the sphere and the seawater. At some point during the fall the density of the prill becomes less than that of the seawater and the prill becomes buoyant and begins to rise back towards the surface. This is usually followed shortly afterwards by the separation of the air bubble from the remaining urea, and the latter resumes sinking.

To allow the prediction of fall depth of approximately spherical soluble particles containing an air bubble, a simple model was developed that takes account of the density variation with dissolution.

The fall velocity at time t can be determined by equating the gravitational force with the retarding drag generated by its passage through the water. Drag coefficients for smooth spheres as a function of Reynolds number were obtained from standard text books.

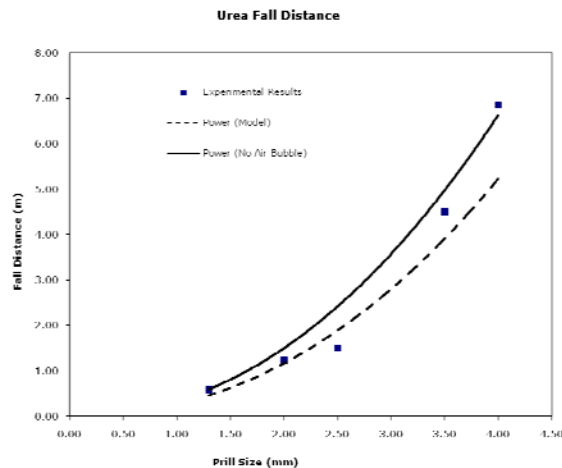


Figure 3: Model and experimental results for urea prills.

Emboldened by the observation that the total time for dissolution was proportional to the diameter of the prill, we assumed the effect of dissolution was to decrease the diameter of the sphere linearly with time. For this application a function for dissolution rate was estimated from experiments conducted with commercially available prilled urea.

The model was run for urea prills in the range of 1.3 to 4 mm diameter, and falling through sea water the results are displayed in Fig 3. The dissolution depth was found to increase strongly with diameter. The model projected only a small decrease in fall depth for prills with air bubbles of the sizes produced in the current manufacturing process.

Observations were made of the fall distance in a vertical cylindrical tube containing seawater for prills of less than 2 mm diameter. Measurements were made in the open ocean for larger size prills. Experimental observations are presented in Fig 3. The density of the prill with air bubble was calculated by determining the volume of alcohol displaced for a given weight. Used in conjunction with the known density of urea the diameter of the air bubble was calculated for various sizes of prill.

VI. Conclusion

The ocean can be used as a sink in which to store the excess carbon dioxide being released into the atmosphere as a result of fossil fuel burning. One method is to increase the amount of carbon dioxide circulating in the ocean organic carbon cycle. The concept of doing this by the addition of nutrients has been examined.

A method is presented that allows the initial "average" concentration required to limit the final biomass to be predicted. It relies on estimating the turbulent diffusion coefficient for the width of the initial injection. Broadcasting from a ship of prilled material manufactured on shore provides an easy method of producing a near uniform concentration of nutrient over a design depth. Using this information the prilling process and injection can be adjusted to optimise the environmental response by creating the lowest initial nutrient concentrations while achieving the desired final concentration of phytoplankton. A simple model allows the depth over which each particle dissolves in the ocean surface mixed layer to be estimated. Prill size can be used to change this depth.

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