A 20 GW Thermal 300-metre^3/sec Wave-energised, Surge-mode Nutrient-pump for Removing Atmospheric Carbon dioxide, Increasing Fish Stocks and Suppressing Hurricanes.

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Abstract

As an outcome of a workshop following Hurricane Katrina this paper extends ideas submitted to the Royal Society Call for Submissions on geoengineering. The frequency and severity of hurricanes rise sharply if the surface temperature of the sea exceeds 26.5 C. This is because of our definition of hurricane categories rather than having anything to do with atmospheric physics. If we can pump warm water downwards to below the thermocline perhaps we can have gentle hurricanes. Designers of overtopping wave plant for energy generation want a high product of head and flow. But the head of water needed to overcome the density difference due to the temperature drop with depth in many hurricane breeding sites is often less than 200 mm. This means that we can use the horizontal movement of sea waves to move water through a wall of non-return valves into an enclosure with a down-tube reaching to the thermocline. The warm water from above will mix with cold, nutrient-rich water, giving a mixture of an intermediate temperature which will rise until is reaches the level of the same density, from where it will spread sideways. If this layer is at 100 metres below the surface there will be enough daylight to allow the growth of phytoplankton. These are efficient carbon absorbers and the start of the marine food chain.

Keywords: Climate change, wave-energy, nutrient pump, thermocline, hurricane suppression, phytoplankton, marine food chain.

1 Wave pumps

There have been several proposals for using waves to pump sea water for energy generation. Some involve water moving over the top of a wall [1] or ramp [2], [3] into a lagoon above sea level with height optimized to maximize the product of head and flow volume. For the hurricane-suppressing project we need a head only just large enough to overcome the density difference between the upper and lower thermal layers.

For a salt concentration of 35,000 ppm and temperature range from 25 C down to 10C this is only 2.76 kg/m^3 so that the head of water needed is very small compared with ocean wave heights. This means that we can use a low freeboard enclosure with a wall of non-return valves. Most of the water will enter horizontally rather than by over topping. A sectional view of the design is shown in figure 1. A vertical non-permeable tube below the valve wall will carry the water down to the thermocline. The lower part will be subject to a gentle, steady hoop tension.

2 Structure

The top of the structure seen in plan in figure 2 is a buoyant ring formed by lashing used tyres in a hexagonal array with buoyancy provide by foamed concrete. Tensile members in the form of spokes made from polypropylene rope can give it strength in the horizontal plane. This gives a structure which can conform to long waves and which has low or, because of the tyres, even a negative material cost.

Hanging at a depth of 17 metres below this is a second ring of tyres containing normal density concrete or bags of gravel for negative buoyancy. The rings are joined by vertical strands of a high tensile glass/Kevlar composite around which are Vee-shaped chlorinated rubber extrusions, shown in figure 3, which can move together to form a low drag foil section or open to make contact with the adjacent extrusion to form a closed valve. Outside the vertical strands are horizontal hoop strands of the full wall diameter which lie in notches in the noses of the foils and pull the vertical strands inwards to give a double curvature. These horizontal hoops will resist the pressure inside the walls.

The downward water velocity is low and so the down tube can be tapered so as to increase velocity with little drag penalty but an increase of momentum force. It can also be tilted to direct the flow to one side. If it carries a series of inflatable tubes it can be raised to adjust its length, for movement in shallow water and for eventual recovery.

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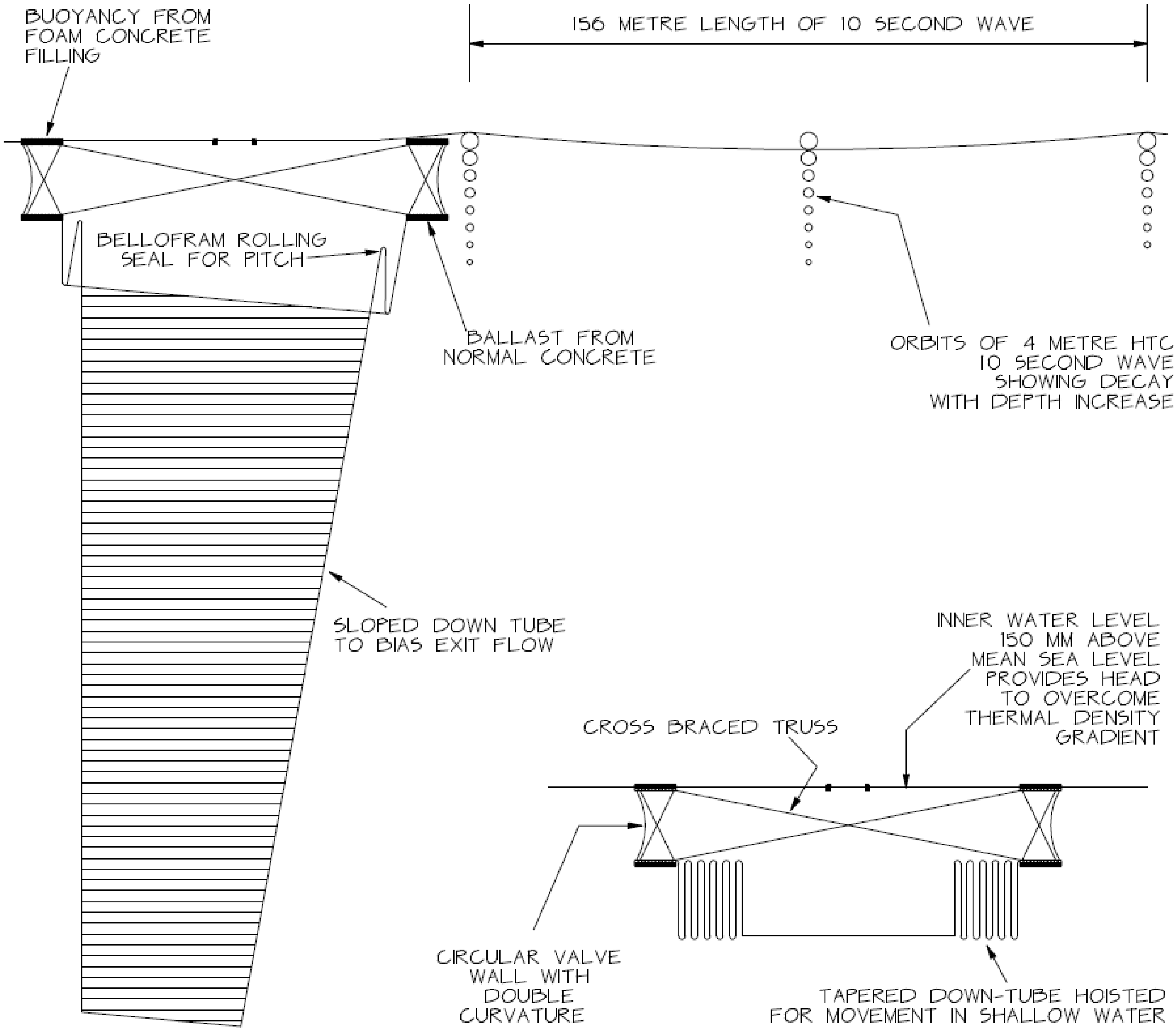

Figure 1. A side view of the wave sink with a tapered down-tube reaching to below the thermocline in working configuration and with its tapered skirt hitched up for transport in shallow water.

It will not be easy to handle a 100 metre diameter 200 metre long tube of thin plastic in air but it will be possible to edge-weld material being unwound from six rolls with axes slightly tilted from the vertical mounted on six rafts joined in a ring. The tube can be lowered into the water as welding progresses and never be separately handled.

Many wave inventors leave moorings and sea bed attachment to the end of the design process and find that the problem is expensive and the installation slow. Wave sinks will be subject to the drag forces of any local current and also to momentum forces proportional to the squares of incident and reflected waves. Furthermore the structure has no strong points to which mooring cables can be connected and we may need to operate in very deep water.

Many ocean currents take the form of large vortices known as gyres. One solution to the mooring problem is not to moor at all. We let the units drift freely but we bias the exit flow to one side so that there is a force tending to move them towards the centre of whichever gyre is to be cooled or enriched. By adjusting the proportion of side flows we can keep them moving round the gyre at any chosen radius from its centre. This looks quite easy in the many gyres of the Caribbean and the two alternating currents along the hurricane-breeding track from West Africa. The Coriolis effect means that there will be a change in the direction of a current with changing depth so the trail of nutrients will diverge from the path of the sink and give good dispersion.

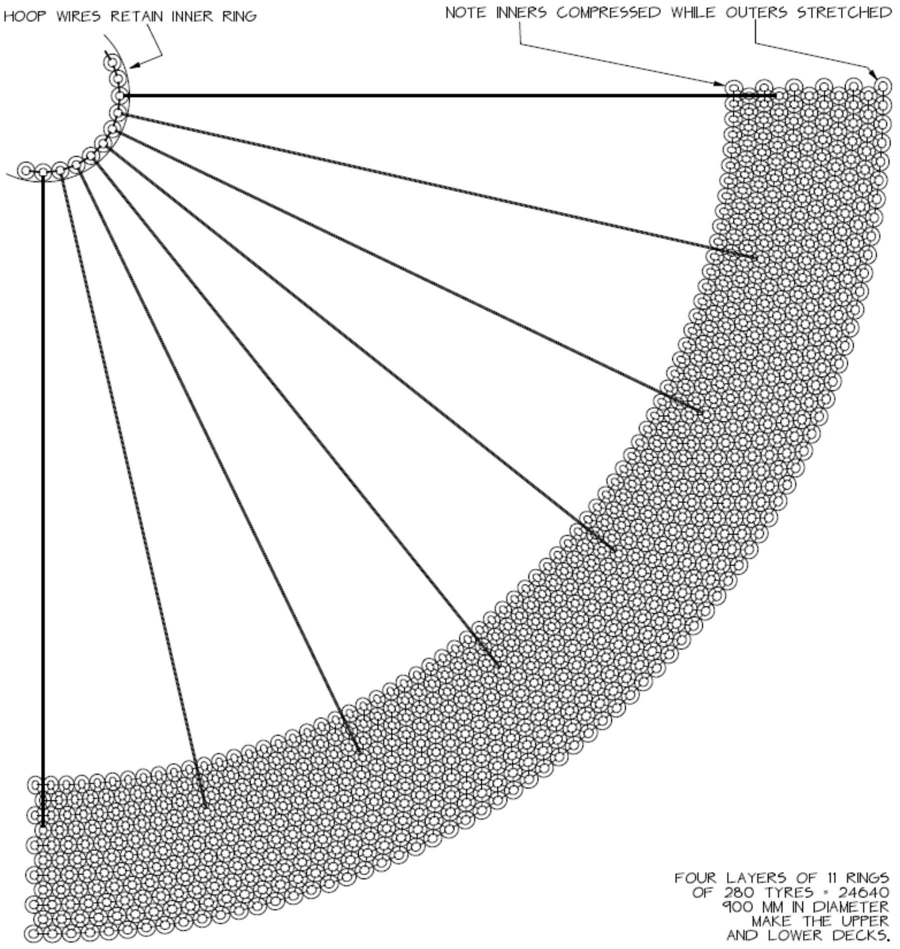

Figure 2. A plan view of the more rigid part of the structure made by lashing rings of used tyres in four layers.

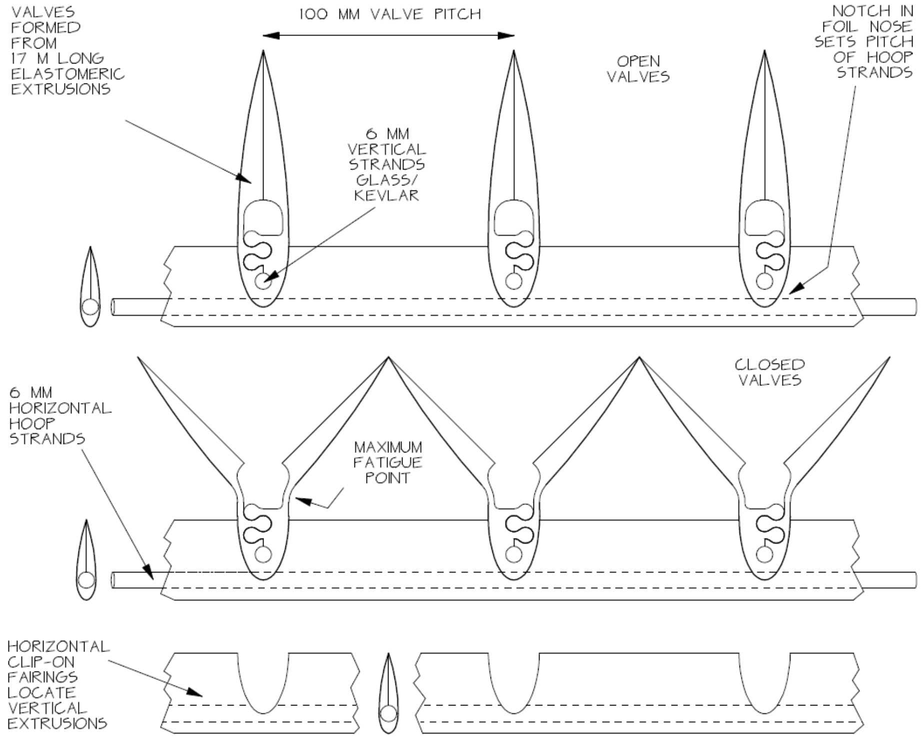

Figure 3. The valve wall uses 17 metre long rubber extrusions clipped to a grid of vertical and hoop wires.

3 Pumping rate

In a deep water wave the particles move in circular orbits with diameters which decay with depth, but the rate of decay is less for longer wave periods. If we integrate the displacements from the surface down to the bottom of the valve wall, multiply by the wave frequency and ignore any effect of standing waves generated by the non-permeable tube below the valve wall, we can estimate water transfer as a function of wall depth for any period.

Figure 4 Plots flow in cubic metres per second, per metre width of valve wall, per metre amplitude of the incident wave for periods of 6 to 10 seconds as a function of the wall depth.

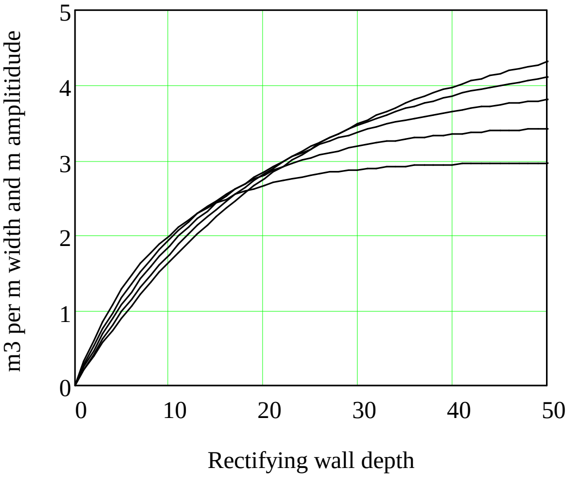

Figure 4. Flow coefficient as a function of wall depth.

This shows that the effect of rapid orbital decay of short waves balances the slower occurrence of long waves at wall depths of about 17 metres, giving a flow of about 2.6 cubic metres a second per metre width and metre amplitude for most of the useful wave periods. If we take the annual wave climate scatter-diagram for Lanzarote, typical of many trade-wind sites, reduce wave amplitudes by 0.15 metres for the thermal head and 0.03 metres for loss through a non-return valve, we find that a 100 metre diameter valve wall will transfer a mean annual flow of about 150 m^3/second. If we multiply this flow rate by the specific heat of sea water and a temperature difference of 15K we get a mean transfer rate of thermal energy of 9.6 GW.

However we can argue that this analysis is conservative because water that enters the enclosure will form the crest of a wave that travels across its diameter until it reaches a closed valve-wall at the opposite side. It will then be reflected and the trough of the resulting anti-node will draw more water into the enclosure. The process will be repeated after another diameter of travel.

If there are no spilling or plunging breakers the transfer of energy by deep water waves to the next part of the sea is extremely efficient. One certain way of making a very efficient wave energy device is to let the water move in same way as it does when driving the next bit of sea with the correct pressures and displacements at each point through the depth but also to prevent the generation of any further waves. For this to happen the water should be driving a purely resistive load with a force in proportion to velocity and with no reactive components.

Most practical wave converters must have the inevitable mechanical inertia of the material of their displacing elements and also some added hydrodynamic inertia if the displacement of the water around them differs from that of an undisturbed wave. The skill of the wave energy designer should be aimed at minimizing total inertia, canceling the remaining inertia at the most useful frequency with a spring term and then providing the correct resistive damping for small and moderate wave heights and periods.

The wall of rectifying valves will present the perfect loading and displacement for half the time but will act as a reflector for the other half of the cycle. It will behave like an electrical transmission cable with the correct matching resistor in series with an ideal diode. This suggests that the conversion of wave energy to pumping energy ought to be nearly 100% for half the time and zero for the other half, an average of 50% less any flow losses caused by pressure drop through valves or leakage from imperfect closure.

When we calculate power from flow and pressure for the valve-wall system described above, the efficiency is only 10%, leaving considerable room for improvement and a question about where the rest of the energy has gone.

A second approach is to suppose that, because for half the time we have the ideal mechanism and for half the time a bad one, the incoming energy will split equally between transmitted and reflected waves. As energy depends on the square of amplitude, the successive internal reflections and transmissions should have amplitudes which are $1/\sqrt{2}$ of the previous wave. This series converges on the value 3.414.

The project needs numerical modeling of internal reflection and tank tests but perhaps we may hope for a flow increase of 2 to 2.5, giving flow rates of 300 to 375 m^3/sec and a thermal transfer of over 20 GW from each 100m unit in a gentle wave climate such as Lanzarote. The larger waves found at higher latitudes might double this.

The valves will open to prevent any inward force. Outward forces will be resisted by the hoop wires and radial ties. It may be possible to design valves which open to relieve unwanted excessive internal pressure.

4 Biological effects

Moving warm water down provides a large but only temporary thermal store. This may be useful for saving New York from the next Katrina but there is a second benefit. Water at the surface will be in carbon dioxide equilibrium with the present-day atmosphere but mixing with water below the thermocline is normally very slow. The deep water has pre-industrial CO2 level. The solubility of CO2 rises with falling temperature and higher pressure so the second effect of the system will be the transfer of some CO2 from the atmosphere to deeper parts of the ocean.

We can influence the amount of mixing by choosing the shape of the bottom tube. A nicely shaped return curve and an outer sleeve will allow warm water to stay close to the down-tube and perhaps rise back to the surface. However vertical slits will give thin planar jets with a large area to mix with the outside water. By filling or emptying water tubes in the slit edges we can change the exit slit geometry and so adjust the mixing ratio.

Numerical models support a conjecture, due to Myhrvold [4], that warm surface water mixed with cold but nutrient-rich thermocline water will rise to the level at which it finds water of its own density and then spread sideways as a ‘density stratum’. Caldeira [5] points out that if the mix is controlled so that the equilibrium point is 100 metres below the surface there will be enough light for the growth of phytoplankton. The biological food chain is a powerful way to move carbon dioxide from the atmosphere to the sea bed without increasing acidity, Behrenfeld et al [6].

Marine productivity is measured in grams of carbon per square metre per year with many mid ocean regions having low rates of 50 gC/m^{2}yr. However in regions with natural upwelling caused by winds moving surface water during a la Niña event the productivity can reach 1000 gC/m^{2}yr. Half the world’s fish are caught in only 1% of the sea area and much of the rest is effectively a marine desert. A wave-driven sink would make a private local la Niña event in any hitherto unproductive region, even in warm seas.

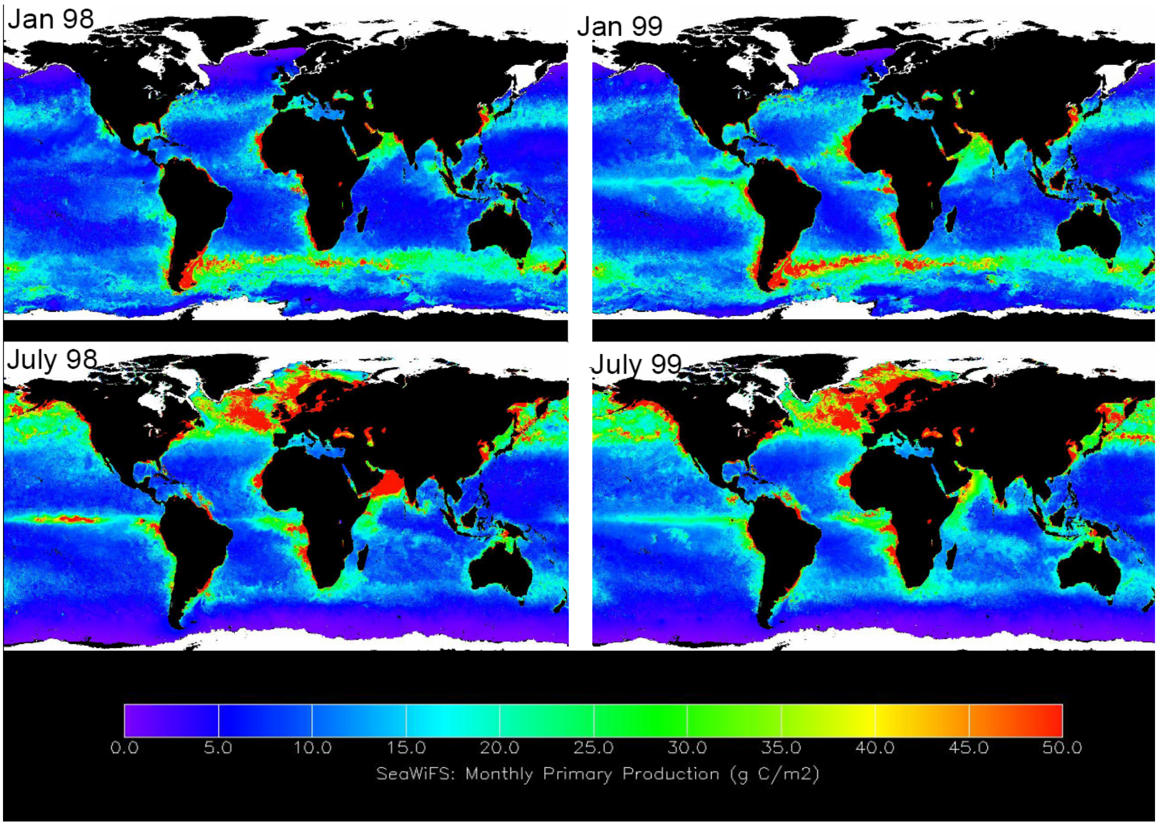

Figure 5. NASA data for monthly marine chlorophyll production expressed as grams of carbon per square metre month. There are quite large changes between years and very large changes between seasons. Most areas of the oceans are effectively deserts because nutrient-rich water cannot move against the density gradient. The ratio of productive to unproductive area is even greater than these maps suggest because of the distortion of the Mercator projection from a sphere to an unrolled cylinder. The area of the world’s oceans is 3.6 x 10^{14} m^2. If just 10% of the oceans could absorb carbon at 250 grams per m^2 year, well below the very best red regions, the annual carbon removal rate would be 9 Gigatonne, close to anthropogenic carbon emissions but in non acidic form. It is interesting to ask what species would be best at converting this enormous biomass to a form that would reach to the deep sea bed. More from http://marine.rutgers.edu/opp/swf/Production/results/all2_swf.html

A steady input of all the natural nutrients all the year round at the right level might be better than intermittent short surges such as those that occur when fertilizers brought down the Mississippi to the Gulf of Mexico producing excessive growth leading to an oxygen shortage.

Provisional estimates for direct carbon removal are between 10^4 and 10^5 tonnes per year from each sink, with a corresponding increase in world fish protein, Caldeira and Wood [7].

The resulting fish production is itself a useful mechanism for carbon removal. Wilson et al [8] write that fish drink sea water continuously and raise its alkalinity to the range pH 8.5 to 9.2. This precipitates calcium and some magnesium as insoluble carbonates. Small fish in warm water are proportionally more productive per unit of body mass. Wilson et al. suggested that the present removal rate is in the range 40 to 110 x 10^6 tonnes of carbon a year. In a subsequent on-line addendum [9] they increase this to 900 x 10^6 tonnes a year with a suggestion that even this might be conservative. It would be interesting to know if wave sinks could increase the productive fraction of the oceans from 1% to say 20%.

5 Conclusions

Although the initial ideas behind this paper arose from a requirement to reduce the frequency and severity of hurricanes it may turn out that wave-driven down-welling may have substantial beneficial effects with regard to CO2 removal and fish production.

Entry of water horizontally through the valve-wall offers the ideal impedance-match for wave energy transfer to a low head enclosure for half the time but will reflect energy for the other half.

This flow pattern must be distinguished from overtopping into the much higher heads needed for power generation.

The thermal energy transferred to the thermocline is far larger than the incident wave energy, even if we ignore the possible extra flow caused by secondary internal reflections.

Mooring problems can be avoided if the units can vary the side to which water is discharged so as to vary their distance from the centre of an ocean gyre.

It may be possible to provide permanent, private la Niña events anywhere in the many large unproductive regions of the oceans and so increase world fish production by an order of magnitude.

The project needs help from marine biologists to advise about which species can be most effective for conversion of the absorbed carbon dioxide.

Acknowledgements

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References

[1] E. Mehlum. Tapchan. In *Hydrodynamics Ocean Wave-Energy Utilization.* Evans DV and Falcao A.F. eds. Springer-Verlag, Berlin, pp. 51–55, 1986.

[2] A. N. Walton-Bott. Power plus proteins from the sea. *J. Royal Society of Arts.* vol 123, pp 486-503, 1975.

[3] J. P.Kofoed and A. Nielsen. The Wave Dragon – evaluation of a wave energy converter. from http://people.civil.aau.dk/~i5jpk/, 1997.

[4] N. Myhrvold. Personal communication. 2008

[5] K. Caldeira. Personal communication. 2008

[6] M. J. Behrenfeld, R. O'Malley, D.A. Seigel, C. R. McClain, J. L. Sarmiento, G. C. Feldman, P. G. Milligan, R. M. Letelier, and E. S. Boss. Climate-driven trend in contemporary ocean productivity. *Nature,* vol. 444, pp 752-753, 2006.

[7] K. Caldeira K and L. Wood. Personal communication, 2008.

[8] R. W. Wilson, F. J. Millero, J. R. Taylor, P. J. Walsh, V. Christensen, S. Jennings and M. Grosell. Contribution of fish to the marine inorganic carbon cycle. *Science,* vol 323 pp 359-361,2009

[9] Wilson RW,et al. addendum to above. www.sciencemag.org/cgi/data/323/5912/359/DC1/1 2009.