Can the solubility pump be enhanced?

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Abstract

Downwelling ocean currents carry carbon into the deep ocean (the solubility pump), and play a major role in controlling the level of atmospheric carbon. The formation of North Atlantic Deep Water (NADW) also releases heat to the atmosphere, which is a major contributor to a mild climate in western Europe. One possible response to the increase in anthropogenic carbon in the atmosphere and to the possible weakening of the NADW is modification of downwelling ocean currents, by an increase in carbon concentration or volume. This paper screens seven possible methods of modifying downwelling currents, including using existing industrial techniques for exchange of heat between water and air. Increasing carbon concentration in downwelling currents is not practical due to the high degree of saturation of high latitude surface water. Two of the methods for increasing the volume of downwelling currents were found to be impractical, and four were too expensive to warrant further consideration. Formation of thicker sea ice shows marginal potential as a means of enhancing downwelling current volume.

Keywords: Solubility pump; NADW; Ocean current; Carbon sequestration; Sea ice making.

1. Introduction

Downwelling ocean currents that carry water from the shallow ocean to the deep ocean, and the offsetting rise of deep water to the surface, play a critical role in the distribution of carbon between the atmosphere and the ocean. The deep ocean is colder and hence denser than the shallow ocean in most parts of the globe, and there is a sharp thermocline that marks the start of the deep ocean. In the absence of downwelling currents, there is negligible water exchange between the shallow and deep oceans.

Carbon moves from the shallow to the deep ocean; the main transport mechanism is through the biological pump, the name given to the rain of biological detritus from the euphotic zone in the shallow ocean. Broecker and Denton [1] noted that in the absence of downwelling currents carbon would build up in the deep ocean and deplete in the atmosphere; this effect is now thought to be a factor in past ice ages. Circulation between the shallow ocean and the deep ocean sweeps cold carbon rich water back to the surface, where the combination of lower pressure and higher temperature causes carbon dioxide to desorb back into the atmosphere. Both the end of the ice age and the Younger Dryas cold wave have been associated with changes in downwelling currents.

Downwelling waters contain dissolved carbon; this effect is called the solubility pump. In pre-industrial times an equilibrium was reached that balanced the downward flow of both dissolved carbon and organic detritus against the release to the atmosphere of carbon from water migrating up from the deep ocean. As industrial activity has increased the concentration of carbon dioxide in the atmosphere, downwelling waters are richer in carbon content compared to their pre-industrial levels. Since the residence time of downwelling water in the deep ocean is on the order of 600 to 1000 years [2], there is a perturbation in the solubility pump that has increased the net flux of carbon into the deep ocean, partially offsetting its anthropogenic increase in the atmosphere.

The North Atlantic ocean has a particular pattern of downwelling water, the so called North Atlantic Deep Water (NADW), that forms part of the ocean conveyor belt [1]. Heat released in forming NADW is critical to the mild climate of Europe, which in turn has resulted in its high population density. 13 to 20 Sverdrups (10^6 m^3/s) of downwelling water form in the GIN area (Greenland, Iceland and Norwegian

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Sea) [3,4]. Water of high salinity (due to high evaporation rates in the Mediterranean and tropical areas) is carried north by surface currents, and loses its heat by convection to the atmosphere and by radiation. Where this high salinity water reaches a temperature near 0^oC, it sinks into the deep ocean. Recently evidence has accumulated that the NADW may be weakening, i.e. its volume may be reducing, perhaps because of an increase in temperature over the ocean [5,6]. A similar observation has been made about the southern downwelling current, the Antarctic Bottom Water (AABW) that forms in the Weddell Sea [7]. This raises concerns about both the impact on European climate and on a possible reoccurrence of a mini-ice age comparable to the Younger Dryas.

This study explores the cost of modifying downwelling currents by human intervention, either by increasing the carbon content of existing currents or changing the flow rate of current. The impact of a change in downwelling currents is quite complex. For example, an increase in the concentration of carbon in downwelling water with no other change in volume of flow would move carbon from the atmosphere into the deep ocean, with an expected residence time of 600+ years. Increasing the volume of downwelling water would sweep more carbon from the deep ocean into the atmosphere. While at first this might seem the wrong step to take in the face of the buildup of anthropogenic carbon in the atmosphere, it might be an appropriate response to a failure of part or all of NADW formation, with its consequence of a colder Europe and the potential of a new ice age. In the absence of better knowledge of the impact of modifying downwelling currents, geoengineering of these currents would be reckless. The purpose of this work is not to endorse prompt action to modify downwelling currents, but rather to complete a preliminary assessment of the cost of modification, to see if further consideration is warranted.

The key processes that occur in the formation of downwelling currents are the transfer of heat from the ocean to the atmosphere and to space, and the transfer of mass between the ocean and the atmosphere as gases are absorbed or desorbed. Numerous industrial processes focus on the transfer of heat and mass between liquids and air, and we assess these techniques for modifying downwelling currents. Specifically, we explore the potential for increasing the carbon content of downwelling currents in the absence of a change in volume of flow, and the potential to increase the flow rate of NADW. In our study flow rate of NADW is increased by cooling of incremental volumes of water through transfer of heat from seawater in the GIN area. A reduction in the formation of NADW would occur by the opposite process, i.e. transferring of heat to the ocean in this region. Since the heat transfer processes would be similar for cooling or heating, the costs associated with cooling ocean water by a given process are a reasonable first approximation of the cost of heating it.

2. Adding Carbon to Existing Downwelling Currents

The ocean conveyor belt exchanges water between the deep and shallow ocean. As deep ocean water moves to the surface it warms, and this plus the lower pressure leads to a loss of carbon dioxide to the atmosphere. As the surface water moves towards the higher latitudes, it cools and absorbs carbon dioxide. The extent to which the surface water absorbs carbon dioxide prior to sinking determines the efficiency of the solubility pump, and hence the amount of carbon carried down into the deep ocean in solution in downwelling waters.

Volk and Hoffert [8] did an elegant analysis to try to predict the efficiency of the solubility pump at a time when carbon content data in high latitudes was limited. Their calculations indicated an efficiency of 12 to 54%, meaning that surface waters had failed to approach equilibrium. Broecker and Peng [9] note that the time for ocean water to equilibrate in carbon content is on the order of a year, partly because carbon is held in seawater in a complex equilibrium of CO_2 gas plus bicarbonate and carbonate ions. Based on this one might expect to find that water in high latitudes is well below saturation in total carbon; however, data on carbon content in seawater from high latitudes indicates the opposite: high latitude seawater is nearly saturated in total carbon.

Table 1 shows averaged values for seawater from multiple samples at different locations in the GIN. These data are representative of many other samples collected in the expeditions to the areas near NADW formation. In each case the surface water is within 1.5% of its saturation level of total carbon (TC) as calculated by the program of Lewis [10], and the average degree of saturation for the 4 sets of samples is 99.5%.

Table 1
High latitude surface seawater properties

Location	T (°C)	S Salinity (ppt)	P (μmol/kg)	Si (μmol/kg)	TA (μmol/kg)	Actual TC (μmol/kg)[a]	pCO_2 (ppm)	Sat. TC (μmol/kg)[a]	% Saturation (Carbon)	$\frac{\partial TCO_2}{\partial T}$ (μmol/kg°C)
(61°N,27°W) to (64°N,36°W)[b]	7.6	35.04	0.7	3.1	2316	2113	*337*	*2124*	*99.48*	*-8.2*
(61°N,19°W) to (65°N,34°W)[c]	8.0	34.73	0.5	2.2	2306	2077	*294*	*2102*	*98.81*	*-8.6*
(62°N,18°E) to (78°N,11°W)[d]	-0.2	34.77	0.8	5.3	2299	2160	*333*	*2162*	*99.90*	*-8.0*
(70°S,17°W) to (72°S,20°W)[e]	-1.6	34.22	1.9	66.2	2272	2155	*353*	*2156*	*99.95*	*-7.6*

a: Saturation TC was calculated using Lewis' program with Roy's constants and total PH values. Italicized values are calculated; normal font values are taken directly from the cited references.
b: Average of 27 samples from [11]
c: Average of 28 samples from [12]
d: Average of 69 samples from [13]
e: Average of 9 samples from [14]

Given the high degree of saturation, the solubility pump would appear to be highly efficient. There is little potential for economically adding dissolved CO_2 to existing downwelling currents as a mechanism of moving incremental carbon from the atmosphere to the deep ocean, since mass transfer near saturation requires excessive contact area. We therefore focus on modification of the flow rate of current.

3. Increasing Downwelling Currents

Creating incremental flow of downwelling currents requires that heat be removed from the ocean. In this paper, we evaluate seven alternatives; as noted above, most of these alternatives could be run in reverse to add heat to the ocean and reduce downwelling currents.

The basis of this study is the formation of one Sverdrup (10^6 m^3/s) of incremental downwelling current in the North Atlantic by transfer of heat from the ocean to the atmosphere during a winter period of 180 days per year. Cooling one Sverdrup (Sv) of seawater from 6 °C to 0 °C requires a heat flux of 25 TW. It is assumed that regardless of where the seawater is returned to the ocean within the GIN it will result in a net incremental downwelling. Seawater properties were based on a blending of results from high arctic samples; we used a heat capacity of 4000 J/kg°C. In cases where mass transfer of CO_2 occurs during cooling, we assume that incrementally cooled surface water takes up an additional 50 μmoles/kg of CO_2 (8.15 μmoles/kg°C), so that the net incremental flux of carbon is 9.6 M tonnes per year or 0.5% of estimated current annual ocean uptake of 1.9 GtC [15]. The atmospheric heat sink in this study is assumed to have an average ambient temperature of -10 °C over the ocean [16,17], and -20°C over land [18]; in each case, average wind speed is assumed to be 10 m/s [19]. All costs are reported in 2000 US dollars. Land based power requirements are met by dedicated power plants, assumed to be nuclear, with an installed cost of $1500/kW and an operating cost of $0.015/kWh [20]. Barge based power requirements are met by wind generators, with an installed cost of $1000/kW [21,22] and an operating cost of $0.01 per kWh [23,24]. The installed cost for wind power includes four hours of battery backup storage; equipment would not operate during longer wind free periods. Note that key assumptions in this screening study would be evaluated in further detail if any of the cases appeared to be worth further evaluation.

Seven methodologies were evaluated for formation of incremental NADW and are summarized in Table 2; each are discussed briefly below.

Table 2
Summary of cases

Case	Carbon flux	Power	Key design parameters	Key cost parameters
1. Forced draft heat exchanger [25,26,27]	Yes	250 GW	• Seawater cooled: 10 m^3/s per cell • Fan power: 1500 kW per cell • Pump power: 1000 kW per cell • Area: 2000 m^2 per cell • Elevation gain for seawater: 8 m	• 10^5 cooling tower cells: $5.2 million per installed cell • Piping: $1100/m (1000m/per cell)
2. Cooling ponds [28,29,30]	Yes	20 GW	• Area: 100,000 – 360,000 km^2	Not estimated because of excessive land requirement
3. Air injection [27,31]	Yes	21 TW	• Air flow rate: 23.6 m^3/s per unit (750 m^3/s required to cool 1 m^3/s of seawater) • Discharge pressure: 121kP • Blower power: 670kW per unit	• 3.2 x 10^7 blowers: $240k per installed unit • Piping: $345/m (500m per unit is assumed)
4. Circulation of warmer layers [32]	Yes	-	-	Not estimated because of insufficient areas of inversion
5. Barged based finned heat exchanger [31,33,34]	No	15 GW	• Seawater cooled: 25 m^3/s per barge • Seawater flow velocity: 1m/s • Finned tube diameter: 2.5cm • Friction loss: 1.4m • Heat transfer coefficient: 577 W/m^2K	• 4.0 x 10^4 barges: $2 million per unit • Heat exchangers: $17.73/$m^2$
6. Modified heat pump [31,33,34]	No	nil	• Seawater cooled: 25 m^3/s per barge • Refrigerant flow rate: 44 kg/s • Finned tube diameter: 2.5cm • Heat transfer coefficient: condenser: 600 W/m^2K; Evaporator: 2000 W/m^2K	• 4.0 x 10^4 barges: $2 million • Modified heat pumps (condenser and evaporator): $17.73/$m^2$
7. Formation of thicker sea ice [34]	Yes	500 MW	• Seawater cooled: 10 m^3/s per barge • Ice formation: 0.081 m^3/s (to cool 1 m^3/s of seawater) • 2 low lift screw pumps and 1 high lift pump per barge	• 8.1 x 10^3 barges: $2 million per unit • Low lift screw pump $0.4M per barge, installed.

1. Conventional forced draft cooling towers:
Cooling towers are the workhorse of the process industries for cooling of water against air, and provide both high heat and mass transfer as water falls through a moving air stream. For this study, forced convection, located at sea level in Greenland or Iceland, was chosen over natural draft to reduce the height to which the ocean water would have to be pumped. Power requirements for this case are very high, 250 GW, to elevate the large volume of water. Heat rejection from power generation would be approximately 500 GW, but this is small compared to the heat flux from the ocean of 25,000 GW.

2. Cooling ponds:
Cooling ponds rely on natural convection over a freestanding body of water rather than forced draft; they accordingly require larger space. We envisioned a daily fill and drain cycle, pumping water into ponds each evening that self drained during the day. Such a cycle would likely prevent formation of a permanent ice cap on the pond, which would impair heat transfer. This case was rejected without further analysis based on the preliminary assessment that the area required would exceed the area of Iceland and be the equivalent of about 1/3rd of the ice free area of Greenland.

3. Air injection:
In this case land mounted fans compress air to a head of about 2 m of seawater. The heat of compression is removed from the compressed air in finned pipe coolers, and the air is injected at -20 ^{o}C and 1.5 m below the surface of the ocean through distribution pipes. The rising air bubbles transfer both heat and CO_2 to the seawater. The volume of air is controlled by the requirement to remove heat from the water. The energy of compression is enormous, requiring 21 TW of power generation.

4. Circulating warmer layers of the ocean to the surface:
One barrier to more effective heat transfer from ocean to atmosphere occurs when a temperature inversion occurs in the ocean. Figure 1 shows two temperature profiles drawn from the US National Oceanographic Data Center [32]. The left hand profile illustrates an inversion, and the right hand profile illustrates a more typical temperature profile. This case envisioned using ship based pumping to physically move warmer water over the cold surface layer, creating a higher temperature gradient between ocean and atmosphere and thus a higher heat transfer rate. Since there is no net change in hydrostatic head, pumping energy would be limited to frictional losses. Two factors led to rejecting this case without further analysis: areas of inversion are too infrequent to make the case practical, and temperature gradients are too small to have a significant impact. An assessment of 83 winter ocean temperature profiles drawn over the period 1990 to 2000 from NODC data showed inversions in 16% of samples, with an average inversion gradient (the difference between the surface temperature and the point of warmest water) of 2.4 ^{o}C.

5. Finned heat exchanger:
To reduce pumping costs, an alternative cooling scheme was developed in which seawater is circulated by barge mounted pumps through finned piping that is above the ocean, then returned to the ocean. With no hydrostatic head loss, pumping energy is limited to overcoming friction. Since there is no direct contact between the seawater being cooled and the atmosphere and since the returned water is presumed to sink due to its lower temperature and higher density, no mass transfer of carbon is assumed to occur in this case. Although the seawater has no net elevation gain, the friction loss in the finned tubes gives a power requirement of 15 GW.

6. Submerged modified heat pump:
Standard heat pumps, including refrigerators, pump heat against a thermal gradient and require a work input, normally in the form of compression. In the case of cooling seawater in winter, the flow of heat is with the thermal gradient, so a modified barge based "heat pump" was considered, in which a refrigerant liquid evaporates in tubes below the sea, and the vapor is cooled and condensed back to liquid in tubes above the sea. Comparable tube geometry was assumed for this case as with Case 5. 40,000 barges are required. Since the seawater being cooled does not directly contact the atmosphere no carbon flux is assumed.

7. Formation of thicker sea ice:
Ice bridges and ice based drilling platforms are based on the formation of thicker ice by pumping of water onto the top of existing ice. The heat transfer rate is enhanced because the insulating effect of the ice, both due to thickness and a reduction in convective heat transfer, is eliminated when water sits on top of ice. This case assumes barges are equipped with wind turbine generators and both low head and high head pumps. Prior to ice formation, the high head pumps would spray water into the atmosphere to speed formation of sheet ice. Once the ice sheet is formed, a low head pump would pump seawater onto the ice to form thicker ice sheets, which would reach a final thickness of 3m. In the springtime, the pumps would continue to circulate ocean water onto the ice sheet to melt the ice, forming additional cold downwelling water. Both the ice forming and ice melting steps have high contact between the atmosphere and seawater, so carbon flux will occur. Because the volume of water flow is 8.1% of 1 Sv (since the latent heat of ice formation contributes to subsequent cooling of seawater during melting), the power requirement is only 500 MW.

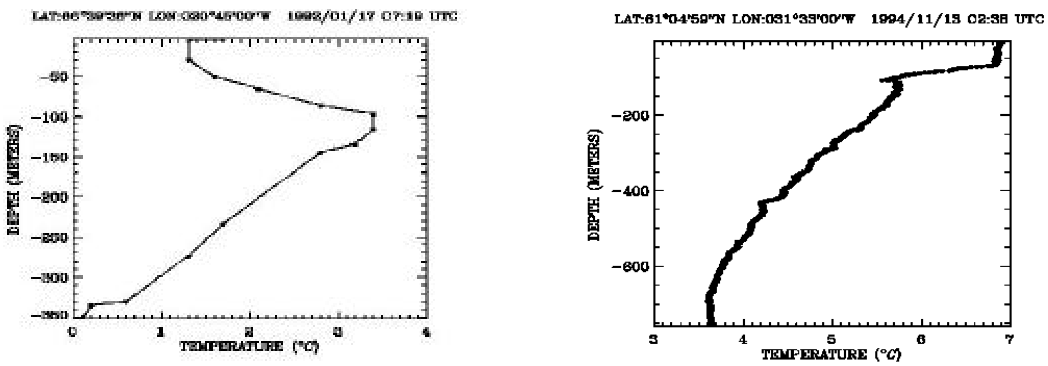

Fig. 1. Typical seawater temperature profiles.

4. Results

Table 3 summarizes the results of an economic assessment of the capital and operating costs of modifying NADW. Cost estimates were only partially developed for cases where the economics were overwhelmingly unfavorable. Results are expressed as $\$/m^3$ of incremental current formed, and as $/GW of heat release. We calculate the latter value based on both the incremental heat flux from the ocean and the total heat flux heat released from power generation (both waste heat and dissipated heat from power consumption). For cases where additional carbon is taken up by the seawater, results are also expressed in $/tonne of CO_2. As noted above, the impact on sequestration of carbon would need further assessment; it is not clear that carrying more dissolved carbon into the deep ocean by an increased current flow actually sequesters that carbon; however, in Table 3 we make this assumption as a means of quantifying the cost per unit carbon.

The results warrant several comments:

- Despite their perceived effectiveness in industrial settings, conventional industrial processes for removing heat from and adding carbon to seawater at a scale significant to ocean currents would require enormous sums of money. These methods, which do not include ice formation, require a very large flow of water; pumping energy requirements are enormous. (Formation of ice significantly reduces the volume of seawater required to achieve a given heat flux, because the latent heat is so much larger than the sensible heat removed from the water.)

- Air injection is the least economic alternative: the power requirements to create the hydrostatic head to inject the air are so large that the process is inherently uneconomic. Air volume requirements are driven by the need to cool seawater, not by the carbon transfer; air's low heat capacity and density relative to water requires that enormous volumes of air must be compressed and cooled prior to injection.

- If the prime driver for modifying ocean currents were as a means of sequestering carbon, then for the case of cooling towers and cooling ponds it would be more effective to build the non-fossil power generation capacity in industrial countries and shut down existing fossil fuel plants rather than to operate the power plants to cool and saturate additional seawater. This observation is expanded below.

- Separation of CO_2 from the fossil fuel combustion flue gas and injection of this CO_2 into the deep ocean provides a benchmark value against which alternative schemes for moving carbon into the deep ocean can be weighed. (As with most other methods for modifying GHG, direct injection of CO_2 into the ocean would require more analysis of the full impact.) The best current indication of the cost of direct injection is $90-180/tonne CO_2 [35,36], further indication of how uneconomic cooling towers, cooling ponds and air injection are for carbon sequestration.

- The least cost alternative for both modifying current and sequestering carbon is the formation of sea ice. Key factors in this case are the low head required for pumping water, typically <0.3 m since 90% of the ice thickness is below sea level, and the reduced volume of flow because heat is lost as latent heat of ice formation, as noted above. We found that only this case warranted further evaluation.

Table 3
Costs of modifying ocean current

Case	$/m^3 of incremental current	$/GW of incremental heat release from ocean	$/GW of total incremental heat release*	$/tonne of incremental CO_2 absorbed
1. Forced Draft Heat Exchange	8×10^{-3}	5	5	4×10^{3}
2. Cooling Ponds	-	-	-	-
3. Air Injection	4×10^{-1}	2×10^{2}	70	2×10^{5}
4. Circulation of Warmer Layers	-	-	-	-
5. Finned Heat Exchanger	1×10^{-3}	1	1	-
6. Submerged Modified Heat Pump	1×10^{-3}	1	1	-
7. Formation of Thicker Sea Ice	1×10^{-4}	9×10^{-2}	9×10^{-2}	>60

* Power generation and consumption included

5. The Limits of Carbon Sequestration

Carbon emissions from a typical coal fired power plant are 0.996 kg of CO_2 per kWh of power generated [37]. If the sole goal of current modification is carbon sequestration, then given the presumed incremental flux in this study of 3.5×10^{10} kg of CO_2 per year, we can calculate an upper limit on the amount of power that should be used to create incremental ocean current. If power requirements for creating incremental carbon uptake in incremental current exceed 4.1 GW then a better alternative is to replace existing coal fired power generation with non-fossil fuel generation. (This limit would not apply if the objective of current modification were climate modification from heat release to or from the atmosphere.) Similarly, if carbon sequestration is the objective then we can calculate a limit on the height to which seawater can be pumped in any scheme to cool seawater that does not involve ice formation. 4.1 GW can elevate one Sv of seawater to a height of 0.4 m with a perfectly efficient pump. Any elevation gain greater than this, as for example is required by cooling towers, is impractical if the sole benefit being pursued is the incremental absorption of carbon, since again replacement of existing coal fired power is the more economic alternative.

6. Conclusion

Geoengineering of ocean currents as a means of climate or GHG modification is costly. Of the seven methods that were preliminarily screened, two were not feasible for technical reasons and only one shows any promise of being in the same cost league as recovery and ocean injection of CO_2 from flue gas from combustion of fossil fuel. If a consensus built to explore climate modification through geoengineering, alternate means of climate modification should be critically assessed against ocean current modification.

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