GEOENGINEERING DOWNWELLING OCEAN CURRENTS: A COST ASSESSMENT

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Abstract. Downwelling ocean currents carry carbon into the deep ocean (the solubility pump), and play a 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 contributor to a mild climate in 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 study assesses the costs of 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 by pumping ocean water onto the surface of ice sheets is the least expensive of the methods identified for enhancing downwelling ocean currents. Modifying downwelling ocean currents is highly unlikely to ever be a competitive method of sequestering carbon in the deep ocean, but may find future application for climate modification.

1. Introduction

Oceans play a major role in climate by two primary mechanisms. First, surface currents transport heat from lower to higher latitudes, where it is released to the atmosphere. In particular, the cooling of surface currents in the North Atlantic contributes to the formation of North Atlantic Deep Water (NADW), and the associated heat release is one factor in the mild climate in northern Europe that enables population at a higher latitude than on other continents (see, for example, Broecker (1997)). The extent to which European climate is influenced by ocean storage, ocean transport, and atmospheric transport has been the focus of recent studies that suggest the impact of ocean transport mechanisms have been overestimated in the past (see, for example, Trenberth and Caron (2001) and Seager et al. (2002)).

Second, the oceans are a vast storehouse of carbon. The deep ocean, for example, is estimated to hold over 38 Tt of dissolved carbon (Prentice et al., 2001). If all current annual anthropogenic carbon were transferred to the deep ocean, the concentration of carbon would increase by 0.018% per year. Movement of carbon into or out of the deep ocean is speculated as a possible factor in major changes in

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climate, such as ice ages and the Younger Dryas period of cool weather (see, for example, Broecker and Denton, 1990).

Carbon moves into the deep ocean by two mechanisms, the biological pump and the solubility pump. The former is the name given to the rain of biological detritus from the euphotic zone in the shallow ocean. In the absence of any circulation between the deep ocean and the shallow ocean, Broecker and Denton (1990) note that carbon accumulates in the deep ocean and depletes in the atmosphere, with related cooling due to a weakening of the greenhouse impact of CO_2.

The solubility pump is the name given to the transport of carbon rich cold water into the deep ocean from downwelling currents that form in areas of low temperature and high salinity (thermohaline circulation). There are two major flows: NADW is formed in the Greenland-Iceland-Norwegian Sea area (GIN), with an estimated flow rate of 13–20 Sverdrup (Sv, 10^6 m^3s^{-1}) (Broecker and Peng, 1992; Dickson and Brown, 1994); high salinity from evaporation in lower latitudes helps form this current. Antarctic Bottom Water (AABW) is formed in the Weddell Sea, with an estimated flow rate of 30–38 Sv (Bolin et al., 1981). Water transport from the shallow to the deep ocean by downwelling currents is offset by upwelling currents and diffusion; the split between these two mechanisms is not fully understood. 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 600–1000 years (Bolin et al., 1981), 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.

There is some evidence of a weakening of downwelling currents (Broecker et al., 1999; Hansen et al., 2001; Segar, 1997). This poses two potential concerns: will it cool European climate because of less heat release from NADW formation, and will it impact the balance of carbon between the atmosphere and the deep ocean? This study looks at the cost of human intervention into ocean circulation patterns by the formation of incremental downwelling current in the GIN. 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. 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 include these techniques for modifying downwelling currents. We note that the impact of incremental downwelling current is not clearly understood; the objective of the study is to quantify the cost as an aid in determining whether there is an economic potential for current modification to impact either European climate or CO_2 sequestration. Clearly, the risk from current modification would require a far deeper assessment of impact if implementation were contemplated.

The disposition of incremental downwelling current is not known, and would require more modeling before any implementation. At one extreme, incremental downwelling current could be offset by an upwelling current that reaches the surface of the ocean, releasing more CO_2 to the atmosphere from the deep ocean than was carried down (since the deep ocean has an even higher concentration of carbon than the high latitude shallow ocean). At the other extreme, the incremental downwelling current could remain in the deep ocean, raising the pycnocline (the line of density demarcation between the shallow and deep ocean) as the ocean stores more cold dense water. (An incremental increase of 1 Sv of downwelling current six months per year (the basis of this study) would raise the pycnocline by about 4 cm per year.) In this study, we assume that incremental downwelling current is retained in the deep ocean; however, if the opposite were true, then one could, for example, reduce downwelling currents if the sole objective were to reduce the release of CO_2 to the atmosphere. Costs for heating water would be comparable to costs for cooling water for most methods reviewed in this work.

2. Adding Carbon to Existing Downwelling Currents

Downwelling currents lead to an exchange of water between the deep and shallow ocean. Deep ocean water that moves to the surface 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 (1985) predicted the efficiency of the solubility pump at a time when carbon content data in high latitudes was limited. Their calculations indicated an efficiency of 12–54%, meaning that surface waters had failed to approach equilibrium. Broecker and Peng (1982) 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 I shows averaged values for seawater from multiple samples at different locations in the GIN and one from the southern ocean. 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

TABLE I
High latitude surface seawater properties

Location	T (°C)	S Salinity (ppt)	P (μmol kg^{-1})	Si (μmol kg^{-1})	TA (μmol kg^{-1})	Actual TC (μmol kg^{-1})	pCO$_2$ (ppm)	Sat. TC (μmol kg^{-1})[a]	% Saturation (Carbon)	$\frac{\partial T\mathrm{CO}_2}{\partial T}$ (μmol kg^{-1} °C^{-1})
(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 Tally et al. (1997).
[c] Average of 28 samples from Brewer and Takahashi (1981).
[d] Average of 69 samples from Clarke et al. (1984).
[e] Average of 9 samples from Heywood and King (1995).

carbon (TC) as calculated by the program of Lewis et al. (1998), and the average degree of saturation for the four sets of samples is 99.5%.

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 study, 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 Sv 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. As discussed above, we assume that this incremental downwelling current is not offset by an equivalent upwelling current but rather causes a net addition to the deep ocean. Cooling one Sv of seawater from 6 to 0 °C requires a heat flux of 25 TW. Seawater properties were based on a blending of results from high arctic samples; we used a heat capacity of 4000 J kg^{-1} K^{-1}. 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^{-1} of CO_2 (8.3 μmoles kg^{-1} K^{-1}, see Table I), resulting in a net annual incremental flux of carbon of 35 Mt CO_2 or 0.5% of estimated current annual ocean uptake of 1.9 GtC (Prentice et al., 2001). The atmospheric heat sink in this study is assumed to have an average ambient temperature of -10 °C over the ocean (Jones et al., 1999; Martin and Munoz, 1997), and -20 °C over land (NCDC, 2002); in each case, average wind speed is assumed to be 10 m s^{-1} (MOST, 2002). All costs are reported in year 2000 US dollars. Land based power requirements are met by dedicated power plants, assumed to be nuclear, with an installed cost of \$1500 kW^{-1} and an operating cost of \$0.015 kW^{-1} h^{-1} (EIA, 2002). Barge based power requirements are met by wind generators, with an installed cost of \$1000 kW^{-1} (Inglis, 1978; Cadogan et al., 1996) and an operating cost of \$0.01 per kWh (DWIA, 2002; NREL, 1996). The installed cost for wind power includes four hours of battery backup storage; equipment would not operate during longer wind free periods.

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

3.1. 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 incremental heat flux from the ocean of 25 TW.

3.2. 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

TABLE II
Summary of cases

Case	Carbon flux	Power	Key design parameters	Key cost parameters
1. Forced draft heat exchanger[a]	Yes	250 GW	• Seawater cooled: 10 m^3 s^{-1} 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^{-1} (1000 m per cell)
2. Cooling ponds[b]	Yes	20 GW	• Area: 100,000–360,000 km^2	Not estimated because of excessive land requirement.
3. Air injection[c]	Yes	21 TW	• Air flow rate: 23.6 m^3 s^{-1} per unit (750 m^3 s^{-1} required to cool 1 m^3 s^{-1} of seawater) • Discharge pressure: 121 kP • Blower power: 670 kW per unit	• 3.2×10^7 blowers: \$240 k per installed unit • Piping: \$345 m^{-1} (500 m per unit is assumed)
4. Circulation of warmer layers[d]	Yes	–	–	Not estimated because of insufficient areas of inversion.
5. Barged based finned heat exchanger[e]	No	15 GW	• Seawater cooled: 25 m^3 s^{-1} per barge • Seawater flow velocity: 1m s^{-1} • Finned tube diameter: 2.5 cm • Friction loss: 1.4 m • Heat transfer coefficient: 577 W m^{-2} K^{-1}	• 4.0×10^4 barges: \$3 million per unit • Heat exchangers: \$17.73 m^{-2}
6. Modified heat pump[e]	No	Nil	• Seawater cooled: 25 m^3 s^{-1} per barge • Refrigerant flow rate: 44 kg s^{-1} • Finned tube diameter: 2.5 cm	• 4.0×10^4 barges: \$3 million • Modified heat pumps (condenser and evaporator): \$17.73 m^{-2}

(*Continued on next page.*)

TABLE II
(*Continued*)

Case	Carbon flux	Power	Key design parameters	Key cost parameters
			• Heat transfer coefficient: condenser: 600 W $m^{-2}K^{-1}$; Evaporator: 2000 W $m^{-2}K^{-1}$	
7. Formation of thicker sea ice[f]	Yes	1.8 GW	• Seawater cooled: 10 m^3 s^{-1} per barge • Ice formation: 0.081 m^3 s^{-1} (to cool 1 m^3 s^{-1} of seawater) • 2 low lift screw pumps and 1 high lift pump per barge	• 8.1×10^3 barges: \$3 million per unit • Low lift screw pump \$0.4 million per barge, installed. • Learning factor: 80%

[a] (Uchiyama, 1976; Chandler et al., 2000).
[b] (Langhaar, 1953; Throne, 1951; Shanahan, 1984).
[c] (Chandler et al., 2000; Peters and Timmerhaus, 1991).
[d] (NODC 2002).
[e] (Peters and Timmerhaus, 1991; Hewitt et al., 1994; TMT, 2002).
[f] (Benford, 1991; Fetchko, 1968; NASA, 2002; ESA, 2002; Erickson et al., 1990).

the area of Iceland and be the equivalent of about one third of the ice free area of Greenland.

3.3. 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 $-10\,^{\circ}$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 set by the requirement to remove heat from the water. The energy of compression is enormous, requiring 21 TW of power generation.

3.4. 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 (NODC, 2002). The left hand profile illustrates an inversion, and the right hand profile illustrates a

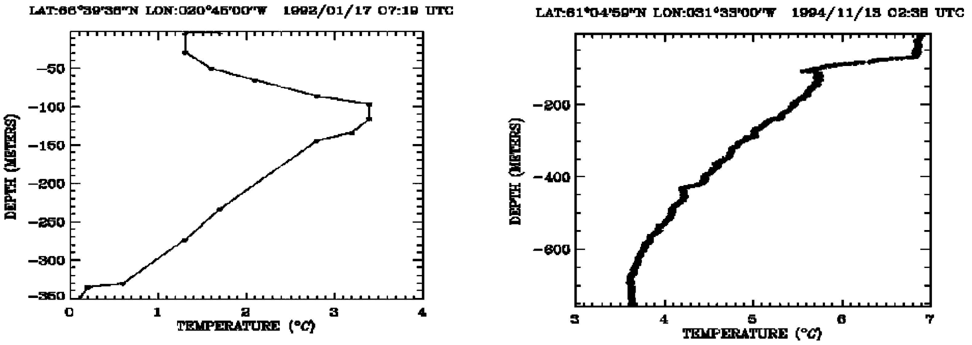

Figure 1. Typical seawater temperature profiles. Source: US NODC (2002).

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 1990–2000 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 °C.

3.5. 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.

3.6. 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. Since the seawater being cooled does not directly contact the atmosphere no carbon flux is assumed.

3.7. 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 seawater sits on top of ice. This case assumes unmanned barges are equipped with a 450-kW nominal wind turbine generator and both low head and high head pumps. High head pumps spray water into the air before the ice sheet is formed, to hasten surface cooling and initial ice formation. Once an ice sheet is formed, low head pumps would discharge seawater onto the ice sheet to thicken it. Average power requirement is 225 kW, sufficient to raise the required amount of water by 1 m.

The spacing between barges would be designed to allow sufficient area to transfer the heat from cooling and freezing of seawater to the atmosphere with a design air temperature of $-10\,^{\circ}$C. In spring, pumps would continue to operate and pump seawater onto the top of the ice sheet to contribute to melting. However, as atmospheric temperatures moved through the freezing point of seawater there would be no significant net heat transfer between the pumped water and the atmosphere, and rather the latent heat required to melt the ice would be transferred from seawater, cooling the seawater (melting would occur both below and above the ice). Given the magnitude of the latent heat of crystallization of water, only 0.081 Sv of water ice would have to be formed into ice to create one Sv of cooled seawater in the springtime.

The assumption that salt is retained in the incremental sea ice is critical to the timing and extent of the formation of incremental current. Sea ice that forms naturally in the ocean does so at the bottom of an ice sheet. In this case, as seawater freezes it results in a brine of increasing salinity that extensively drains to the ocean through micro channels in the bottom of the ice sheet (see, for example, Wadhams, 2000). This accounts for the lowered salt content of sea ice relative to seawater. However, Wadhams (2000) notes that ice closer to the top of an ice sheet is more likely to retain brine and can also precipitate solid salts. Data is not available on the disposition of salt when sea ice is formed from the top down. We believe that if seawater freezes on top of an ice sheet salt would mainly be trapped on the surface or within the ice, both as brine cells and solid salts, especially as the thickness of ice built up to several meters thick. If this were the case, then incremental downwelling current would occur when the sea ice melted in the spring, since the melting ice would lower the temperature of seawater and the salinity would be unchanged.

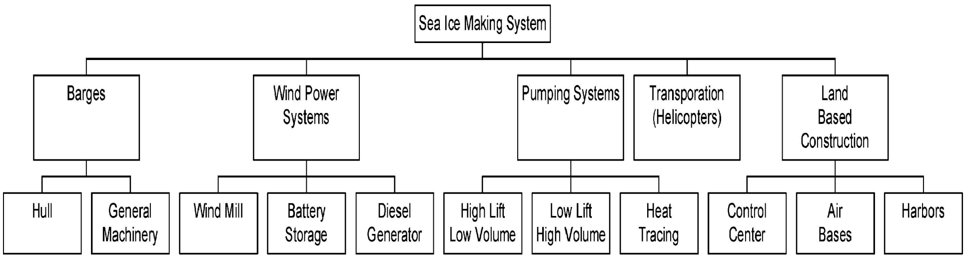

Figure 2. Scope and estimate breakdown structure for sea ice formation.

If, contrary to this assumption, brine was able to flow from the top of the ice sheet back into the ocean in the winter as incremental sea ice was formed, then incremental downwelling current would occur in the winter driven by salinity. However, the melting incremental ice in the spring would reduce surface ocean salinity and retard downwelling currents, since the lower salinity would decrease the density more than the temperature drop would increase it. While the brine would create incremental downwelling current in the winter, the multiplier effect that arises from the latent heat of the formation of the ice would not be realized. Hence, a critical assumption in this work that would require experimental confirmation prior to further design is that salt is indeed trapped and retained in an ice sheet when seawater is pumped onto it and freezes.

An initial screening estimate indicated that one method, formation of sea ice, had a significantly lower cost than the other alternatives. This case was then further developed, i.e. a more detailed definition of scope was prepared for only this case. The scope and estimate breakdown structure is shown in Figure 2. The more detailed scope includes power storage of 4 h to give a short operating reserve and a further reserve for deicing through electrical heat tracing. Pumping would be terminated during periods of no wind in excess of a few hours. Barges are towed into position each fall by tug and remain self-positioned with a propulsion system until frozen into sea ice. Barge spacing is set so that ice sheets reach a final thickness of 7.5 m, with 0.75 m above sea level. (More detailed calculation of heat transfer coefficients would be required to confirm the validity of barge spacing at the next stage of conceptual design.) Barges are equipped with data collection and transmission systems, including remote troubleshooting. Maintenance in season is provided by land based helicopters stationed at four sites in Greenland and Iceland; these sites also provide summer storage and maintenance of the barges. Both the ice forming and ice melting steps have high contact between the atmosphere and seawater, so carbon flux will occur, although as noted above heat transfer between seawater and the atmosphere occurs preferentially in winter due to the temperature difference between air and ocean. Because the volume of water flow is 8.1% of 1 Sv the total power requirement is only 1.8 GW. Because much of the construction is repetitive, a learning factor is applied for barges and equipment installed on them (NASA, 2002).

TABLE III
Costs of modifying ocean currents

Case	\$ m^{-3} of incremental current	\$ kW^{-1} of incremental heat release from ocean	\$ kW^{-1} of total incremental heat release[a]	\$ $tonne^{-1}$ 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	4×10^{-4}	2×10^{-1}	2×10^{-1}	177

[a] Power generation and consumption included.

Details of the capital and operating cost estimate for incremental sea ice formation are shown in the Appendix.

4. Results

Table III summarizes the capital and operating costs of modifying NADW; Cases 1, 3, 5 and 6 are based on a preliminary screening estimate, and Case 7 is based on the more detailed scope and estimate. Capital costs were annualized based on a 10% time value of money and a project life of 30 years. 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^{-1} 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 \$ $tonne^{-1}$ of CO_2.

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, provided it retains its salt content, 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, and only 8% of the incremental downwelling current needs to be frozen as ice. In addition, the pumping head is low because 90% of the ice thickness is below sea level.

- 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 air injection 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^{-1} CO_2 (Fujioka et al., 1997; Summerfield et al., 1993), further indication of how uneconomic cooling towers and air injection are for carbon sequestration.
- If a discount rate of 6%, typical of the cost of borrowing for major public projects, is used instead of 10%, the cost of creating 1 m^3 of downwelling current by the formation of sea ice drops from \$0.0004 m^{-3} to \$0.0003 m^{-3}.
- Early stage conceptual estimates such as this study have a low degree of accuracy, and ultimate estimates often deviate from initial estimates by a range of -50% to $+100\%$ (AACE 1997). However, even given this high degree of potential error, the cost estimate for sea ice formation is so much less than alternatives that we can conclude with confidence that it is the preferred methodology of those studied.

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 (Spath et al., 1999). If the sole goal of current modification is carbon sequestration, then given the presumed incremental flux in this study of 35 Mt 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 currently exceed 4.1 GW, i.e. are greater than 120 W tonne^{-1} yr^{-1}, 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 replacement of existing coal fired power is the more economic alternative.

6. Discussion and Conclusions

The estimates in this study are conceptual and are developed with a minimum of engineering development of scope, and hence are subject to a wide range of error. Nevertheless, some clear conclusions can be drawn from this work.

First, two of the seven methods identified in this study are not feasible for technical reasons: there is not enough free land area to use a cooling pond to cool seawater, and temperature inversions in the ocean are insufficient in frequency and magnitude to make pumping of warmer lower layers to the surface of the ocean practical.

Second, modifying downwelling ocean currents is highly unlikely to ever be a competitive method of sequestering carbon in the deep ocean. The estimated cost for the most favorable case is so high compared to alternatives with less uncertainty that pursuit of this alternative for carbon sequestration is not attractive.

Third, it might be important at some point to enhance downwelling currents for climatic reasons. There is evidence today that NADW is weakening, with a possible impact on European climate. Further, one possible climatic “doomsday” scenario is that global warming could continue to cause a reduction in both NADW and AABW. Although this is an initial byproduct of a warmer climate, a great reduction in these current streams would likely lead to a period of cold weather due to a reduction in heat release from cooling currents and a reduction in the return flux of carbon from the deep ocean to the atmosphere. In this situation it is conceivable that human intervention to try to maintain downwelling currents would be explored. As noted above, much more detailed modeling of oceans and climate would be required to estimate the full impact of current modification. In addition, a critical assumption that salt can be retained in sea ice formed on top of an ice sheet would need confirmation. Since formation of incremental sea ice has a cost much less than half that of any alternative, it should be a focus of future research if geoengineering of ocean currents is pursued. The capital cost of creating one Sv of incremental downwelling current, approximately $45 billion, may appear large, but is well within the public spending capability of the industrialized world, or even northern Europe alone.

Appendix: Capital and Operating Cost Estimate for Formation of Sea Ice

Cost estimates were developed based on a more detailed scope than the initial screening study. Costs were broken into five categories: barges, wind power, pumping, transportation (helicopters), and land based construction (harbors for barge storage and maintenance, and air bases for helicopters). Table AI summarizes key unit cost elements for building one of each system and shows the overall capital cost estimate, which has an all in cost of \$45 G (all currency is Year 2000 US dollars). A "learning factor" of 80% was applied to barge, wind power and pumping costs, i.e. because 8100 units are being built, we assume that capital cost savings of 20% will be identified in such a large production run as compared to building a single unit. Table AII summarizes key operating costs for formation of incremental sea ice, totaling \$1.3 G per year. For references, see note f in Table II.

TABLE AI
Capital costs for sea ice formation

Category	Element	No. of units	Unit cost w/o learning factor (\$ k)	Learning factor	Overall cost (\$ M)
		Direct costs			
Barges	Material	8100	\$1,900	0.8	\$28,000
	Labor (\$50 hr^{-1})	8100	\$1,100		
	Overhead and profit	8100	\$1,300		
Wind power	Installed wind power system	8100	\$450	0.8	\$3,500
	Battery bank	8100	\$90		
Pumping	Low volume pump	8100	\$30	0.8	\$3,500
	High volume pump	16200	\$200		
	Heat tracing and insulation	8100	\$120		
Transportation	Helicopter	32	\$1000	1	\$32
Land based construction	Control center and instrumentation	1	\$70,000	1	\$990
	Harbor and harbor machinery	4	\$100,000		
	Air base	4	\$130,000		
		Indirect costs			
Engineering and supervision	5% of direct costs	1	\$1,700	1	\$1,700
Contingency	20% of direct costs	1	\$6,900	1	\$6,900
Total					\$45,000

TABLE AII

Operating and maintenance costs for sea ice formation

Category	Element	No. of units	Estimate basis	Unit cost (\$ k yr^{-1})	Overall cost (\$ M yr^{-1})
Barges	Tug rent	8100	• \$300 h^{-1}; • Deployment and retrieval: 1440 hrs • 1 tugboat per 20 barges	\$20	\$730
	Maintenance	8100	1% of direct costs	\$40	
	Insurance	8100	1% of total costs (barge, wind power and pumping system)	\$30	
Wind power	Wind turbine and battery O & M	8100	\$0.015 kW^{-1} h^{-1}	\$15	\$200
	Battery replacement	8100	10 years lifespan	\$10	
Pumping	Pump O & M	8100	3% of capital costs	\$10	\$240
	Heat tracing O & M	8100	20% of capital costs	\$20	
Transportation	Helicopter maintenance	32	15% of capital costs	\$150	\$26
	Fuel consumption	32	• \$0.2 liter^{-1} • 230 liters per flight hour	\$70	
	Labor and overhead[a]	32		\$580	
Land based construction	Control center	1	• Building and equipment maintenance: 5% of capital costs • Total man-hrs (\$75 hr^{-1}): 5400 yr^{-1}	\$5,100	\$99
	Harbor	4	• Docks and machinery maintenance: 5% of capital costs • Total man-hrs (\$75 hr^{-1}): 151200 yr^{-1} per harbor	\$17,000	
	Air base	4	• Runway, control tower, and machinery maintenance: 5% of capital costs • Total man-hrs (\$75 hr^{-1}): 3240 yr^{-1} per base	\$6,500	
Total					\$1,300

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